

# Robust machine layout design under dynamic environment: dynamic customer demand and machine maintenance

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**Abstract.** The layout of manufacturing facilities has a large impact on manufacturing performance. The layout design process produces a block plan that shows the relative positioning of resources that can be developed into a detailed layout drawing. The total materials handling distance is commonly used for measuring material flow. Manufacturing systems are subject to external and internal uncertainties including demand and machine breakdowns. Uncertainty and the rerouting of material flows have an impact on the material handling distance. No previous research has integrated robust machine layout design through multiple periods of dynamic demand with machine maintenance planning. This paper presents a robust machine layout design tool that minimises the material flow distance using a Genetic Algorithm (GA), taking into account demand uncertainty and machine maintenance. Experiments were conducted using eleven benchmark datasets that considered three scenarios: preventive maintenance (PM), corrective maintenance (CM) and both PM and CM. The results were analysed statistically. The effect of several maintenance scenarios including the ratio of the number of machines with period-based PM (PPM) to the number with production quantity-based PM (QPM), the percentage of machines with CM (%CM), and a combination of PPM/QPM ratios and %CM on material flow distance were examined. The results show that designing robust layouts considering maintenance resulted in shorter material flow distances. The distance was decreased by 30.91%, 9.8%, and 20.7% for the PM, CM, and both PM/CM scenarios, respectively. The PPM/QPM ratios, %CM, and a combination of PPM/QPM and %CM had significantly resulted in the material flow distance on almost all datasets.

Keywords: Machine layout, robust design, preventive and corrective maintenance, dynamic demand, Genetic Algorithm.

## 1. Introduction

The costs related to material handling are typically 20%-50% of total manufacturing operating expenses. Effective layouts can reduce material handling costs by at least 10-30% (Tomkins et al. 2010). The total distance travelled by materials is a commonly used proxy for measuring the efficiency of layouts (Drira et al. 2007).

Changes to the manufacturing environment may be caused by internal or external factors which disrupt the efficient flow of materials (Kulturel-Konak, 2007). External uncertainties include: variations in customer demand and product mix; changes to product design; shorter product life cycles; the discontinuation of products; or the introduction of new products (Sahin & Turkbey, 2009). Internal disturbances, such as machine breakdowns, reduce the number of available machines which can cause queuing that leads to uneven workload, longer flow-time, lower productivity and higher production costs. When flow is disrupted, downstream resources may be starved of work-in-process which can reduce utilisation. Maintenance activities may be planned or corrective 'fix it when it breaks' (Waeyenbergh & Pintelon, 2009). Both types of maintenance

reduce the number of machines available, which can disrupt flow. With preventative maintenance production plans can take into account downtime, whereas corrective maintenance occurs randomly and needs to be addressed through control actions. To maintain production performance, alternative routings may be adopted to avoid interruption, but the flow distances may increase.

There is a substantial literature on the facilities layout problem and there have been several comprehensive reviews. Kusiak and Heragu (1987) surveyed formulations of the FLP and algorithms for solving deterministic problems. Meller and Gau (1996) reviewed methodologies, objectives, algorithms, and extensions that considered a time element (dynamic layout), uncertainty (stochastic layout) or multiple evaluation criteria (multi-criteria, robust or flexible layout). Dynamic layout problems take into account changes in material handling flow over multiple periods. Robust layouts aim to accommodate changes without the need for expensive reorganisation, whereas the re-layout approach produces a series of layouts for the various periods (Kulturel-Konak, 2007). Balakrishnan and Cheng (1998) presented an early review of the dynamic facilities layout literature, which categorised research according to: equal/unequal size departments; deterministic/stochastic material flow; and the algorithms adopted. Drira et al. (2007) surveyed the literature on facilities layout problems using a framework that included: the type of manufacturing system; facility shapes; layout configuration; material handling system; layout formulation; constraints; and optimisation methods. Kulturel-Konak (2007) reviewed research relating to dynamic and stochastic facility layout problems. Hosseini-Nasab et al. (2018) reviewed 250 FLP-related papers published during the period 1987-2016 and applied a hierarchical classification based upon: layout evolution (static/dynamic); workshop characteristics (shape and dimensions, flow movement, type of manufacturing system and materials handling approach); problem formulation (objective function, problem representation, modelling approach, type of data, constraints); and resolution approaches (multi-objective, multi-attribute, single objective). However, the literature has not considered the integration of the FLP with machine maintenance, which is the research gap that is addressed by this paper.

The objectives of this paper are to: (i) review the literature on facilities layout design, uncertainties in production and maintenance policies; (ii) outline the Genetic Algorithm-based Layout Design (GALD) tool that was developed to solve robust machine layout design problems for systems that are subject to demand uncertainties and maintenance; (iii) describe the experimental design that was used to test the robust design approach with corrective, preventative and combined maintenance regimes; and (iv) investigate how the number of unavailable machines in each maintenance scenario affects the material flow distance.

Section 2 critically reviews appropriate literature. Section 3 outlines the development of the Genetic Algorithm tool for solving facilities layout problems, which is integrated with maintenance planning. The experimental results are presented in section 4. Section 5 provides a discussion and highlights the conclusions of the work and identifies opportunities for future research.

## **2. Literature review**

Drira et al. (2007) and Kulturel-Konak (2007) published comprehensive reviews of the facilities layout problem literature. A systematic review was undertaken using the ISI Web of Science database covering the period 2007 to May 2018 to identify the current status of the literature and research gaps. The initial searches used the keywords “layout design” and “facility layout” and found 308 papers. The definition of the facilities layout problem and its categorisation are presented in section 2.1. The 308 papers were carefully screened to identify those relevant to dynamic layout design. The problem characteristics and the solution approach of the selected papers are shown in section 2.2.

## 2.1 Facilities layout problem

Azadivar and Wang (2000, p.4369) defined the facilities layout problem (FLP) as “the determination of the relative locations for, and the allocation of, the available space among a number of workstations”. Singh and Sharma (2006, p.425) stated that “the output of the FLP is a block layout that specifies the relative location of each department. The detailed layout of a department can also be obtained later by specifying aisle structure and input/output point locations which may include flow line and machine layout problems”.

The FLP may be considered to be a static plant layout problem (SPLP), which produces an optimal layout that suits the current state of business (Rosenblatt, 1986). However, when there are changes over time, it is important to design facilities that can quickly and effectively adapt (Yin & Khoo, 2011). The dynamic plant layout problem (DPLP) involves the design of facility layouts based on a multi-period planning horizon. During this horizon, the material handling flows between pairs of departments in the layout may change (Balakrishnan & Cheng, 2009). It is necessary to determine an appropriate layout for each period, during which it is assumed that the flow data remains constant (Drira et al., 2007). The DPLP may be either a deterministic or stochastic problem. The decision on whether to change the layout should take into account the costs associated with material flow and the rearrangement of the layout (Rosenblatt, 1986). There are two alternative approaches to solving the DPLP: the agile approach which assumes low rearrangement costs and relocates machines from time-to-time; and the robust approach that assumes high relocation costs and aims to minimise total material handling costs in all periods using a single layout (Pillai et al. 2011). Kouvelis et al. (1992, p.287) defined a robust layout as “one that is ‘good’ (or close to optimal) for a wide variety of demand scenarios even though it may not be optimal under any specific demand scenario”. A robust layout design procedure attempts to minimise the total expected material handling costs over a specific planning horizon (Yang & Brett, 1998), so there is no rearrangement cost. To maintain the shortest material flow distance, the layout can be periodically redesigned. However, this has an impact on production time and costs due to facility movement and interrupted production. It may also require specialised labour and equipment, especially for large-size or heavy facilities (McKendall, et al. 2006).

The DPLPs have been formulated as mathematical models. Balakrishnan (1992) presented the formulation for department layouts during the planning horizon with budget constraints and assumed equal-sized facilities. This model was adapted by Balakrishnan and Cheng (1998), McKendall et al. (2006), Rezazadeh et al. (2009), Sahin and Turkbey (2009), and Ulutas and Islier (2009). The flexible machine layout with dynamic environments was formulated as a quadratic assignment problem, in which unequal-size machines and machine position constraints (vertical or horizontal) were considered (Yang & Brett, 1998). Dunker et al. (2005) and McKendall and Hakobyan (2010) considered the dynamic facility layout problem with unequal-area departments using a mixed-integer linear programming formulation. Baykasoglu et al. (2006) studied the budget-constrained dynamic layout problem. Kia et al. (2012) used a mixed-integer non-linear programming model to design a dynamic cellular manufacturing system layout.

Facility layout design (FLD) problems are complex and non-deterministic polynomial time hard (NP-hard) problems (Pourvaziri & Naderi, 2014), which means the amount of computational time required to find a solution increases exponentially with problem size. Efficient metaheuristics have therefore been widely used for solving FLPs, including: Genetic Algorithms; Simulated Annealing; Tabu Search; Ant Colony Optimisation; Particle Swarm Optimisation; and Biogeography-Based Optimisation (Sooncharoen et al., 2015). Genetic Algorithms have been a popular approach to solving facility layout design problems. Kia et al. (2014) found that GA can find near-optimal solutions in much less computational time than CPLEX software for almost all problems. Lenin et al. (2013) demonstrated the effectiveness of GA for solving a single-row layout design problem. The results obtained from GA were more favourable than other approaches. Dapa et al. (2013) reported that GA outperformed the Bat Algorithm and Shuffled Frog Leaping

Algorithm in a multiple-row layout design. Vitayasak and Pongcharoen (2016) investigated the affects of breakdown maintenance and provided a cost-based decision framework for re-layout investment.

## 2.2 Facilities layout design with uncertainties

Table 1 presents 74 of 308 FLP articles which considered uncertainties due to external and/or internal variabilities. There were 55 papers that only considered variability in customer demand. Demand profiles may be represented by material flow matrices, probability distributions, or empirical data. Internal factors include the number of machines, set up time, facility size, routing flexibility, machine maintenance, processing time, waiting time, human factors, and machine reliability.

There were only 10 papers that considered only internal variabilities: Azadeh et al. (2016) that used a fuzzy multivariate approach to optimise the FLP with ambiguous data; Azimi and Soofi (2017) which applied Artificial Neural Networks and a hybrid non-dominated Genetic Algorithm to optimise layout and material handling; Chae and Regan (2016) that considered heterogeneous area constraints; Chang et al. (2013) who considered cell formation, layout and intercellular sequences with flexible routings; Dong et al. (2009) which considered the adding/removal of machines during each period; Khaksar-Haghani et al. (2013) that applied Genetic Algorithms for optimising multi-floor layouts with alternative process routings and flexible configurations; Li et al. (2018) who used an Artificial Bee Colony algorithm for optimising layout taking into account human factors; Neghabi et al. (2014) which adopted an adaptive algorithm for generating robust facility layouts without predetermining the length and width of departments; Salmani et al. (2015) that used Mixed Integer Linear Programming and considered dynamic and uncertain values for the dimensions of departments; and Wang et al. (2016) which considered layout design with unreliable machines. Only 9 papers studied both external and internal variabilities in FLP. There has been no previous research that has considered layout problems with dynamic demand and machine maintenance. This is the research gap considered by this research.

Table 1 Problem characteristics based on demand profiles, dynamic conditions, layout configurations, and optimisation methods

| Authors                       | External factors |                       |                |               | Internal factors   |             |               |                     |                     |                 |              |               |                     |                | Robust layout design | Re-layout design | Approaches                             |
|-------------------------------|------------------|-----------------------|----------------|---------------|--------------------|-------------|---------------|---------------------|---------------------|-----------------|--------------|---------------|---------------------|----------------|----------------------|------------------|--|
|                               | Flow matrix      | Distribution function | Empirical data | Not explained | Number of machines | Set up time | Facility size | Routing flexibility | Machine maintenance | Processing time | Waiting time | Human factors | Machine reliability | Ambiguous data |                      |                  |  |
| Abedzadeh et al. (2013)       | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | GAMS software, PVNS algorithm          |
| Altuntas and Selim (2012)     |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Rule-based data mining                 |
| Asl et al. (2016)             |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Covariance matrix adaptation evolution |
| Asl and Wong (2017)           | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Modified Particle Swarm Optimisation   |
| Ayodeji et al. (2017)         |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Dynamic Programming                    |
| Azadeh et al. (2014)          |                  | /                     |                |               |                    |             | /             |                     |                     |                 |              |               |                     |                | /                    | /                | Data Envelopment Analysis Algorithm    |
| Azadeh et al. (2016)          |                  |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     | /              | /                    | /                | Fuzzy multivariate approach            |
| Azevedo et al. (2017)         | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Quadratic programming                  |
| Azimi and Saberi (2013)       |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Hybrid Particle Swarm Optimisation     |
| Azimi and Soofi (2017)        |                  |                       |                |               |                    |             |               |                     | /                   | /               | /            |               |                     |                | /                    | /                | Artificial Neural Network hybrid GA    |
| Balakrishnan and Cheng (2009) |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Heuristic and Dynamic Programming      |
| Bozorgi et al. (2015)         |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Tabu Search                            |
| Chang et al. (2013)           |                  |                       |                |               |                    |             |               | /                   |                     |                 |              |               |                     |                | /                    | /                | Tabu Search                            |
| Chae and Regan (2016)         |                  |                       |                |               |                    |             | /             |                     |                     |                 |              |               |                     |                | /                    | /                | Linear Programming                     |
| Chan and Malmberg (2010)      |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Monte Carlo simulation                 |
| Chen (2013)                   |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Hybrid Ant Colony Optimisation         |
| Chen and Lo (2014)            | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Ant Colony Optimisation                |
| Cheng et al. (2016)           |                  |                       | /              |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulation, Analytic Hierarchy Process |
| Dong et al. (2009)            |                  |                       |                |               | /                  |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Modified Simulated Annealing           |

| Authors                               | External factors |                       |                |               | Internal factors   |             |               |                     |                     |                 |              |               |                     |                | Robust layout design | Re-layout design | Approaches                                |
|---------------------------------------|------------------|-----------------------|----------------|---------------|--------------------|-------------|---------------|---------------------|---------------------|-----------------|--------------|---------------|---------------------|----------------|----------------------|------------------|---|
|                                       | Flow matrix      | Distribution function | Empirical data | Not explained | Number of machines | Set up time | Facility size | Routing flexibility | Machine maintenance | Processing time | Waiting time | Human factors | Machine reliability | Ambiguous data |                      |                  |   |
| Drira et al. (2013)                   |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Fuzzy Evolutionary Algorithm              |
| Emami and Nookabadi (2013)            | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | GA, Differential Evolution, and SA        |
| Fazlelahi et al. (2016)               |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Permutation-based GA                      |
| Ghosh (2016)                          |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | GA and SA                                 |
| Guan et al. (2012)                    | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Revised electromagnetism-like mechanism   |
| Hanafy and ElMaraghy (2015)           |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Phylogenetic networks                     |
| Hosseini and Seifbarghy (2016)        |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Multi-objective water flow like algorithm |
| Hosseini et al. (2014)                | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Neighborhood Search and SA                |
| Hosseini-Nasab and Emami (2013)       |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Hybrid Particle Swarm Optimisation        |
| Jithavech and Krishnan (2010)         | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulation, Genetic Algorithm             |
| Kaveh et al. (2014)                   |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | GA and fuzzy Simulation Algorithm         |
| Khaksar-Haghani et al. (2013)         |                  |                       |                |               |                    |             |               | /                   |                     |                 |              |               |                     |                | /                    | /                | Improved GA                               |
| Kheirkhah and Bidgoli (2016)          | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Competition algorithm and SA              |
| Kheirkhah et al. (2015)               | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | PSO and Co-evolutionary Algorithms        |
| Kia et al. (2012)                     |                  | /                     |                | /             |                    |             |               | /                   |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing                       |
| Kia et al. (2013)                     |                  |                       | /              | /             | /                  |             |               | /                   |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing                       |
| Kia et al. (2014)                     |                  |                       | /              |               |                    | /           |               |                     |                     |                 |              |               |                     |                | /                    | /                | Genetic Algorithm                         |
| Kia et al. (2015)                     |                  |                       |                | /             |                    | /           |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing                       |
| Kovács and Kot (2017)                 | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Kanban principle                          |
| Krishnan et al. (2009)                |                  | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Genetic Algorithm                         |
| Kulturel-Konak and Konak (2015)       |                  |                       |                | /             |                    |             | /             |                     |                     |                 |              |               |                     |                | /                    | /                | Hybrid SA                                 |
| Kumar and Singh (2017)                |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Score-based two-phase heuristic approach  |
| Li et al. (2018)                      |                  |                       |                |               |                    |             |               |                     |                     | /               |              |               |                     |                | /                    | /                | Artificial Bee Colony algorithm           |
| Liu et al. (2017)                     | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Combination of algorithm and heuristics   |
| Manoochehri and Mohammadjafari (2017) |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulation technique                      |
| Mazinani et al. (2013)                |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Genetic Algorithm                         |
| McKendall and Hakobyan (2010)         | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Tabu Search / Boundary Search Heuristic   |
| Mohammadi and Forghani (2014)         | /                |                       |                | /             |                    |             |               | /                   |                     |                 |              |               |                     |                | /                    | /                | Genetic Algorithm                         |
| Moslemipour and Lee (2012)            | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing                       |
| Moslemipour et al. (2017)             | /                |                       |                | /             |                    | /           |               |                     |                     |                 |              |               |                     |                | /                    | /                | Dynamic Programming / Simulated Annealing |
| Nageshwaranier et al. (2013)          | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Symbiotic Algorithm and Clonal Algorithm  |
| Neghabi et al. (2014)                 |                  |                       |                |               |                    |             | /             |                     |                     |                 |              |               |                     |                | /                    | /                | Adaptive algorithm                        |
| Nematian (2014)                       | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | A modified Branch and Bound method        |
| Pillai et al. (2011)                  | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing                       |
| Pourvaziri and Naderi (2014)          | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | GA and SA                                 |
| Pourvaziri and Pierreval (2017)       | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Cloud-based multi-objective SA            |
| Rabbani et al. (2017)                 |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | SA, PSO, and Hybrid PSO                   |
| Rezazadeh et al. (2009)               | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Improved Particle Swarm Optimisation      |
| Sahin and Turkbey (2009)              | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing (SA) and Tabu Search  |
| Salmani et al. (2015)                 |                  |                       |                |               |                    |             | /             |                     |                     |                 |              |               |                     |                | /                    | /                | Mixed integer linear programming          |
| Samarghandi et al., (2013)            | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Fuzzy Tabu Algorithm                      |
| Shafigh et al. (2017)                 |                  |                       | /              |               | /                  |             |               | /                   |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing (SA)                  |
| Tavakkoli-Moghaddam et al., (2007)    | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Branch-and-Bound approach                 |
| Tayal and Singh (2017)                | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Integrated Firefly and SA-based approach  |
| Tayal et al. (2017)                   | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | SA, Chaotic SA, Hybrid SA and MADM method |
| Turanoğlu and Akkaya (2018)           | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Hybrid Bacterial Foraging Optimisation    |
| Ulutas and Islier (2015)              | /                |                       | /              |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Clonal Selection based algorithm          |
| Ulutas and Islier (2009)              | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Clonal Selection Algorithm                |
| Vitayasak and Pongcharoen (2018)      | /                | /                     |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Teaching-Learning-Based Optimisation      |
| Vitayasak et al. (2017)               | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Backtracking Search Algorithm and GA      |
| Wang et al. (2017)                    |                  |                       | /              |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Mixed Integer Programming                 |
| Wang et al.(2016)                     |                  |                       |                |               |                    |             |               |                     |                     |                 |              | /             |                     |                | /                    | /                | Queueing Theory                           |
| Xiao et al. (2017)                    | /                |                       |                |               |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Problem Evolution Algorithm               |
| Zhao and Wallace (2014)               |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Simulated Annealing                       |
| Zhao and Wallace (2016)               |                  |                       |                | /             |                    |             |               |                     |                     |                 |              |               |                     |                | /                    | /                | Myopic approach                           |
| This work                             | /                | /                     | /              |               |                    |             |               | /                   | /                   |                 |              |               |                     |                | /                    | /                | Genetic Algorithm                         |

### 2.3 Machine breakdown

Machine breakdown has been one of the most studied disruptions in flexible job shop scheduling (Nouiri et al., 2017). The machine failure rate has been represented by the Poisson distribution (Schemeleva et al. 2012) or generated randomly (Nodema et al. 2011). Machine lifetime is commonly modelled using the Weibull distribution (Fitouhi & Noureldath, 2012). The mean-time-to-failure has been represented by the normal distribution or the exponential distribution (Schemeleva et al., 2012). Corrective maintenance has also been considered in the context of robust scheduling for a flexible job-shop scheduling problem (Xiong et al. 2013). In terms of production scheduling, machine breakdown is stochastic, whereas preventative maintenance is planned (Sbihi & Varnier, 2008).

### 2.4 Preventive maintenance policies

Machines are subject to deterioration with usage and age. There is a substantial literature on maintenance that was reviewed by Garg and Deshmuth (2006). Preventive maintenance (PM) comprises “a series of tasks performed at a frequency dictated by the passage of time, the amount of production or machine condition” (Garg & Deshmukh, 2006, p.214). PM refers to “all actions performed in an attempt to retain a resource in a specified condition by providing systematic inspection, detection, and prevention of incipient failures” (Wang, 2002, p.470). Under a periodic policy, a unit is preventatively maintained at fixed time intervals and repaired if there are intervening failures, this is called fixed period maintenance or time-based maintenance (Safari & Sadjadi, 2011). Figure 1 illustrates customer demand (D) changes over time period (P). PM policies can be periodic or based upon production quantities. In Figure 1a, periodic-based PM (PPM) is scheduled every two periods. In Figure 1b, the maintenance operations are performed according to a predefined production quantity (Q), known as production quantity-based PM (QPM), which is scheduled in periods 3 and 5. This policy is growing in popularity in industrial environments because these policies can decrease the cost of maintenance activities, which may be the largest part of an operational budget (Safari & Sadjadi, 2011).

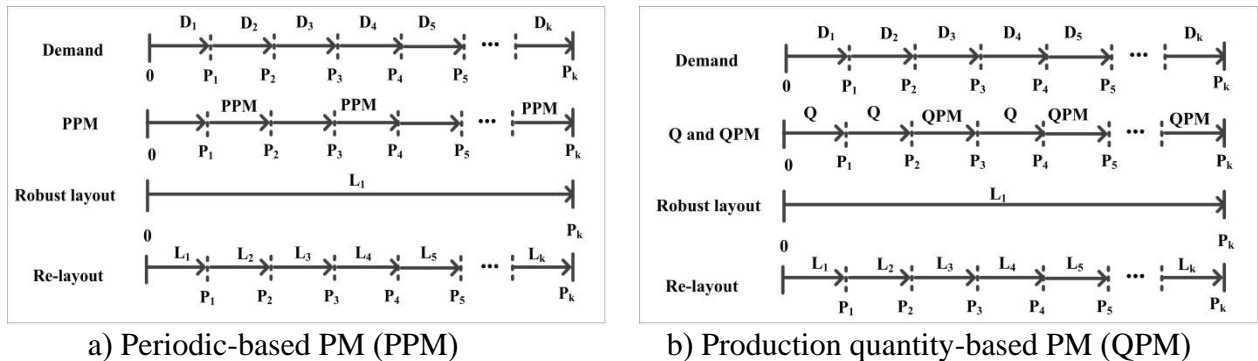


Figure 1 Relationship between layout design approaches and type of preventive maintenance

### 2.5 Routing flexibility

Flexibility was defined as “the ability to effectively respond to change” (Buzacott & Mandelbaum, 1985, p.405). Flexibility helps address internal disturbances arising from machine breakdowns, variable task times, queuing delays, rejects and rework (Sethi & Sethi, 1990). There are eleven different types of flexibility: machine, material handling, operation, process, product, routing, volume, expansion, program and market. The flexibility to use alternative machines or routings helps mitigate problems with material flow that can arise when a particular machine becomes unavailable. Byrne and Chutima (1997) considered alternative machines to be those that could perform the same operations; whilst alternative routings could perform the same sequence of operations. A system with alternative production routes (flexible routes) can maintain high

productivity when some machines have broken down or are under maintenance (Chang, 2007). Routing flexibility has been recognised as a fundamental characteristic of a manufacturing system's overall flexibility, as it enhances a system's ability to produce a given set of part types or part families without interruption. When routings are altered, material flow time and distances are likely to change.

### 3. Genetic Algorithm for solving layout design problem

The Genetic Algorithm (GA) is a population-based, nature-inspired algorithm (Goldberg, 1989; Holland, 1962). A set of candidate solutions is generated as an initial set of solutions, which then undergoes an evolutionary search process. GAs use probabilistic transition rules to guide a highly exploitative search and also performs a multiple directional search by maintaining a population of potential solutions. In each iteration (generation) of the search process the crossover operator helps the GA move towards a local optimum (Hicks, 2006), whereas the mutation operator tends to move the search to a new neighbourhood which leads to increased diversity (Hicks, 2006; Islier, 1998).

In this work, a GA was adopted for solving the facilities layout design (FLD) problem. The GA-based layout design tool includes both robust and re-layout design approaches for dealing with uncertainties that arise from dynamic customer demand and machine maintenance (based on three scenarios: only preventive maintenance, only corrective maintenance, and both preventive and corrective maintenance).

The GA pseudo-code for the proposed robust Facility Layout Design (FLD) problem shown in Figure 2 has the following steps:

- i) problem encoding - chromosomes are produced that comprise a list of genes (each representing a machine number) ; the number of genes in each chromosome is equal to the number of machines to be arranged (see Figure 3);
- ii) load the input data - the number of machines (M), the dimensions of machines (width:  $M_w$  x length:  $M_L$ ), the number of products (N), the machine sequences ( $M_s$ ) and the preventative maintenance (PM) plan for each machine;
- iii) specify the Genetic Algorithm parameters: the population size (Pop), the number of generations (Gen), the probability of crossover ( $P_c$ ), the probability of mutation ( $P_m$ ), floor length ( $F_L$ ), floor width ( $F_w$ ), the gap between machines (G), the number of periods (P) and the percentage of machines that require corrective maintenance ( % CM) per period. All parameters can be identified via the user interface window of the program as shown in Figure 4;

```

Input problem dataset (M,  $M_w$ ,  $M_L$ ,  $M_s$ , N, PM plan)
Create demand level ( $D_{gt}$ ) for each product associated with demand distribution
Randomly generate a list of machines requiring corrective maintenance according to %CM
Set attributes of the problem considered ( $F_L$ ,  $F_w$ , G, P, %CM)
Set GA parameters (Pop, Gen,  $P_c$ ,  $P_m$ )
Randomly generate initial population (Pop)
Set a = 1 (first generation)
While a ≤ Gen do
    For b = 1 to cross (cross = round (( $P_c$  x Pop)/2)), perform crossover operations
    For c = 1 to mute (mute = round( $P_m$  x Pop)), perform mutation operations
    For each chromosome, arrange machines row by row based on  $F_L$ ,  $F_w$  and G
    Replace the machines in maintenance with alternative machines
    For d = 1 to P, calculate material flow distance based on robust layout
    Perform elitist selection
    Chromosome selection using roulette wheel method
    a = a + 1
End loop while
Output the best solution

```

Figure 2 Pseudo code of GA for robust FLD

|   |   |    |   |   |    |   |   |   |   |   |    |    |    |
|---|---|----|---|---|----|---|---|---|---|---|----|----|----|
| 5 | 2 | 10 | 6 | 7 | 12 | 4 | 9 | 8 | 1 | 3 | 11 | 13 | 14 |
|---|---|----|---|---|----|---|---|---|---|---|----|----|----|

Figure 3 Chromosome representation (gene represents a machine number)

Genetic Algorithm for Modeling Layout Problem Program

Genetic Algorithm

Type of layout: ☐ Static layout ☒ Robust layout ☐ Dynamic layout

Number of periods:

Machine layout is evaluated using: ☒ Total Distance ☐ Total Cost

Do you have the breakdown maintenance? ☐ Yes ☒ No

Parameters

Population size:

Number of generation:

Probability of crossover:

Probability of mutation:

Crossover operation\*:   
 (\* 1 = AEX, 2 = CX, 3 = DX, 4 = ERX, 5 = EERX, 6 = IPX, 7 = LOX, 8 = MPX, 9 = 1PX, 10 = OX, 11 = PMX, 12 = PBX, 13 = SCX, 14 = 2PCX, 15 = 2PEX, 16 = 2PECX)

Crossover to population ☐ Replace ☒ Enlarge

Mutation operation:   
 (\* 1 = CIM, 2 = E2ORS, 3 = IM, 4 = SOM, 5 = 3OAS, 6 = 3ORS, 7 = 2OAS, 8 = 2ORS,

Random seed value:

Percent of elitist :  %

Layout Area

Width of area:  meters

Length of area:  meters

Gap between machines:  meter(s)

Run Genetic Algorithm Reset Exit

Identify number of machines for BM in each period

Would you like to consider the breakdown maintenance in the plan ? ☐ Yes ☒ No

Percentage of number of machines for BM in each period:

OK

Figure 4 User interface window of the program

- iv) create the demand levels for each product in each period ( $D_{gk}$ );
- v) randomly generate a list of machines that require CM according to the %CM;
- vi) randomly generate initial chromosomes according to population size ( $Pop$ );
- vii) apply crossover and mutation operators to generate new offspring considering  $P_c$  and  $P_m$ . The two-point centre crossover operator (illustrated in Figure 5a) and two-operations random swap mutation operator (see Figure 5b) were applied in this work.



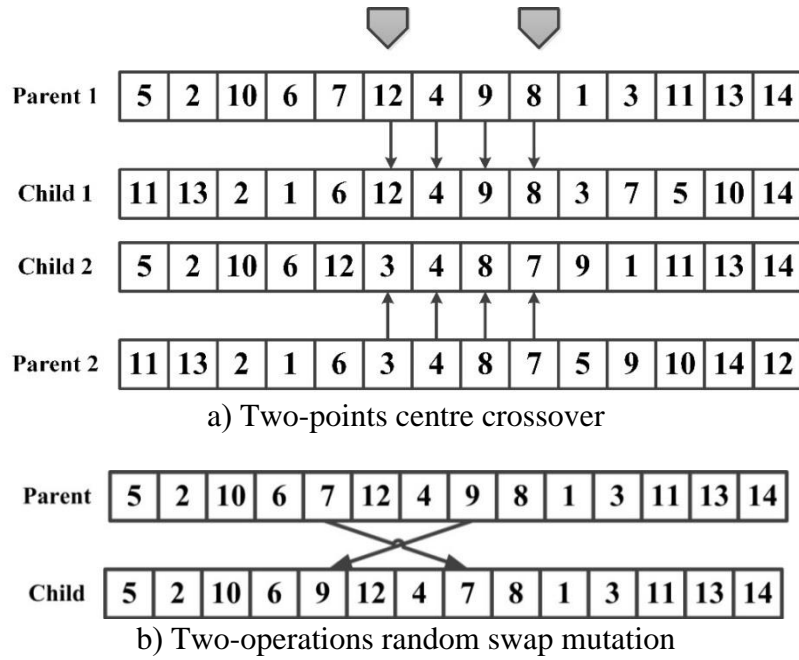


Figure 5 Mechanism of genetic operators (Murata & Ishibuchi, 1994)

viii) arrange the machines sequentially row-by-row, from left to right, starting at the first row and taking into account  $F_L$  with a gap (G) between adjacent machines. The machine width is parallel to the x-axis. The machine length is parallel to the y-axis. Figure 6 illustrates the placement of the machines relating to the genes in the child chromosome shown in Figure 5b).

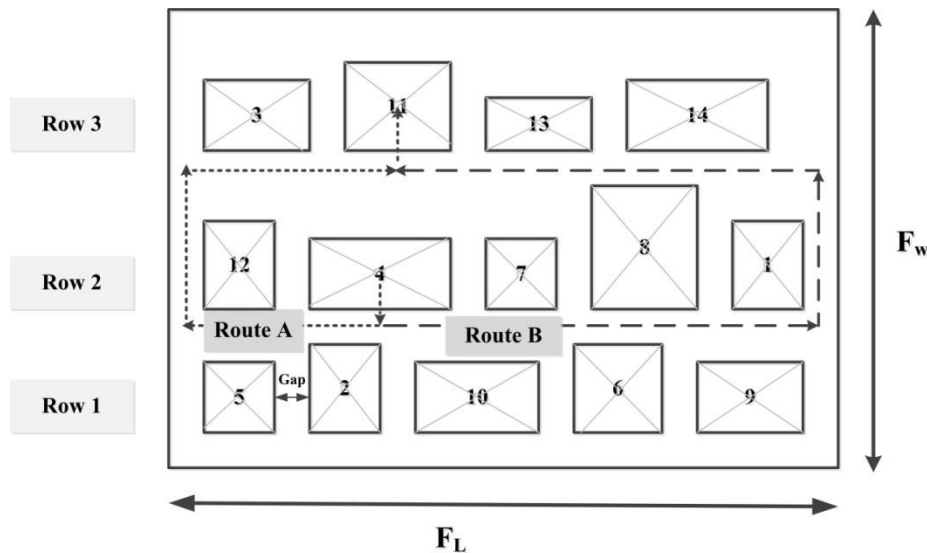


Figure 6 Example of multiple-row machine layout design (Vitayasak & Pongcharoen, 2015)

When there is not enough space for placing the next machine at the end of the row, it is placed in the next row. If floor width ( $F_w$ ) is insufficient, the program will report the extra space required for placing all of the machines. Vehicles moving between rows move from the left or the right side of the row and then up or down to the destination row. The flow distance was evaluated for the shortest route. For example, there are two routes from machine 4 to machine 11; route A would be selected as it is shorter.

ix) replace the machines in maintenance with alternative machines;

Once a machine becomes unavailable, for example being under maintenance, an alternative machine with same type will be prioritised first. Otherwise, a set of pre-defined alternative machines types (e.g. lower-classed machines) will be selected to cover all of the operations for the unavailable machine. The processing route is changed to reflect the alternative machine(s). For example,

Figure 7 assumes the machine sequence 1-2-3. The total material handling distance is MFD1. If machine 3 is unavailable, machine 11 can be used as an alternative, leading to the sequence 1-2-11. The distance for this route is MFD2. When machine 3 is available again the sequence returns to 1-2-3. If the lower-classed machine can only perform some of the operations required, a second alternative machine may be required to cover the remaining operations performed on the unavailable machine. Figure 7 provides an example. If machine 8 and machine 9 (8-9) are alternative machines for the unavailable machine 3, the new machine sequence is 1-2-8-9.

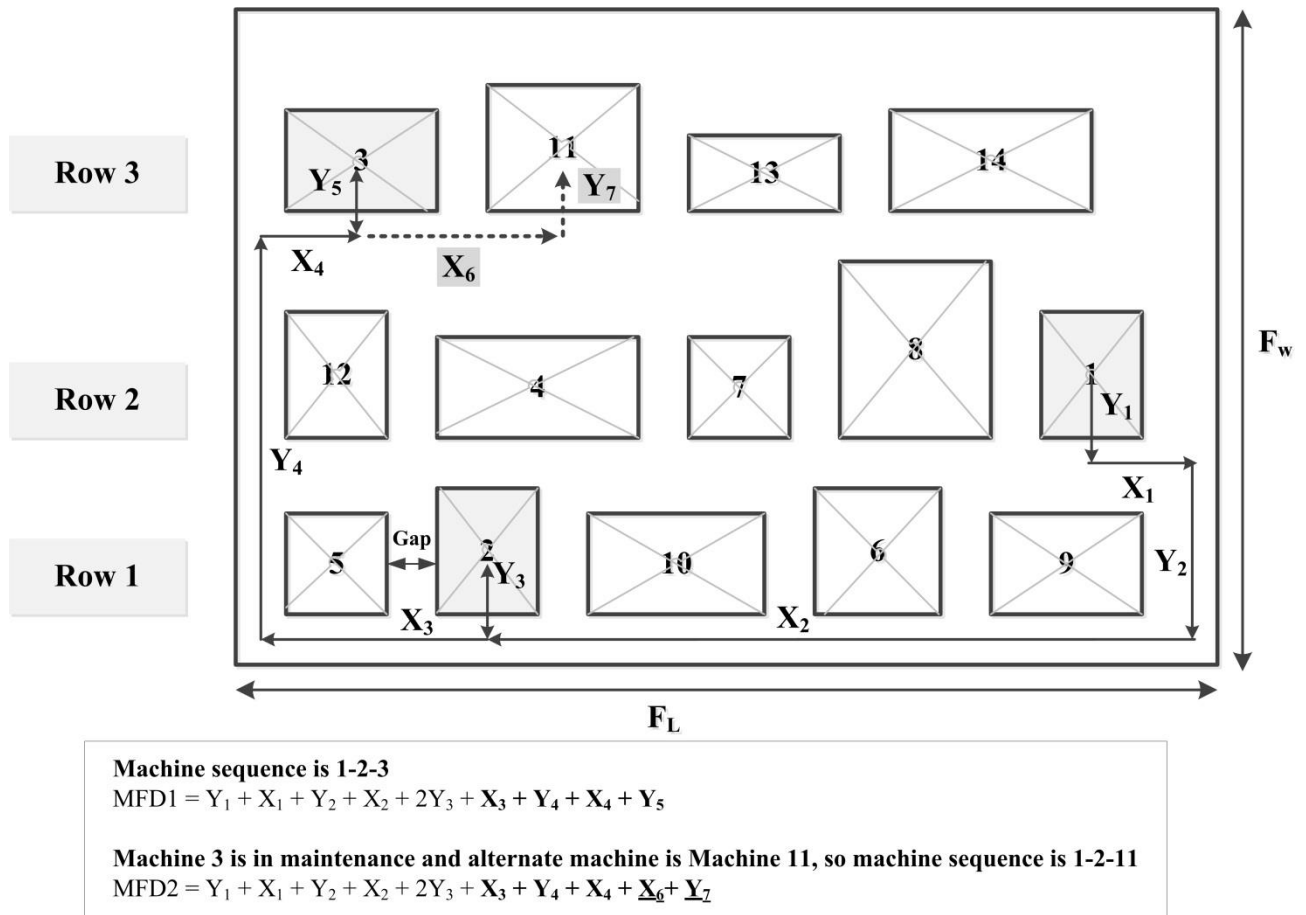


Figure 7 Example of changes in the processing route and material flow distance

x) calculate the fitness value (material flow distance) for chromosome (a) in each period (d) by applying the fitness function. The fitness function (Z) for the efficiency of robust layout design minimises total material flow distance (MFD) as defined by Eq. (1). In case of machine maintenance, equation (1) is still valid for determining the total material flow distance (MFD\*) but the added star symbol “\*” differentiates the maintenance case with alternative machines from the case without maintenance or alternative machines (MFD).

$$\text{Minimise } Z = \sum_{i=1}^M \sum_{j=1}^M \sum_{g=1}^N \sum_{k=1}^P d_{ijgk} f_{ijgk} D_{gk}, \quad (1)$$

$M$  is the number of machines,  $i$  and  $j$  are machine indexes ( $i$  and  $j = 1, 2, 3, \dots, M$ ) ( $i \neq j$ ).  $N$  is the number of product types,  $g$  is a product index ( $g = 1, 2, 3, \dots, N$ ) and  $P$  is the number of time periods,  $k$  is a time period index ( $k = 1, 2, 3, \dots, P$ ).  $d_{ijgk}$  is the material flow distance for product  $g$  from machine  $i$  to  $j$  in period  $k$ ,  $f_{ijgk}$  is the frequency of material flow for product  $g$  from machine  $i$  to  $j$  in period  $k$ , and  $D_{gk}$  is the customer demand for product  $g$  in period  $k$ .

The following assumptions were made to simplify and formulate the problem: 1) material handling between machines is operated via pick-up and drop-off points (P/D points) located at the machines' centroids; 2) the material flow distance between P/D points was measured from the front of machines; 3) the machines were arranged in multiple rows; 4) each machine had either one alternative machine or a group of alternative machines; 5) in case of a random breakdown, an available alternative machine is used during the time period; 6) automated guided vehicles move on rectilinear lines **along the perimeter of the shop floor**; 7) the gap between machines is constant; 8) preventive maintenance plans are periodic (PPM) or based upon production quantities (QPM); and 9) for the QPM, the maintenance operations are performed when the summation of customer demand equals the predefined production quantity.

xi) select elite chromosomes according to percentage of sorted chromosomes (%Elite) in Eq. 2 using the elitist selection mechanism. The chromosomes are sorted according to the material flow distance (MFD). The best chromosome has the shortest MFD;

$$\text{Elite chromosome} = \% \text{Elite} \times \text{Population size (Pop)} \quad (2)$$

The elitist selection mechanism (Figure 8) reproduces the best %Elite chromosomes in the next generation, which is used in step xii). A value of 10% was used.

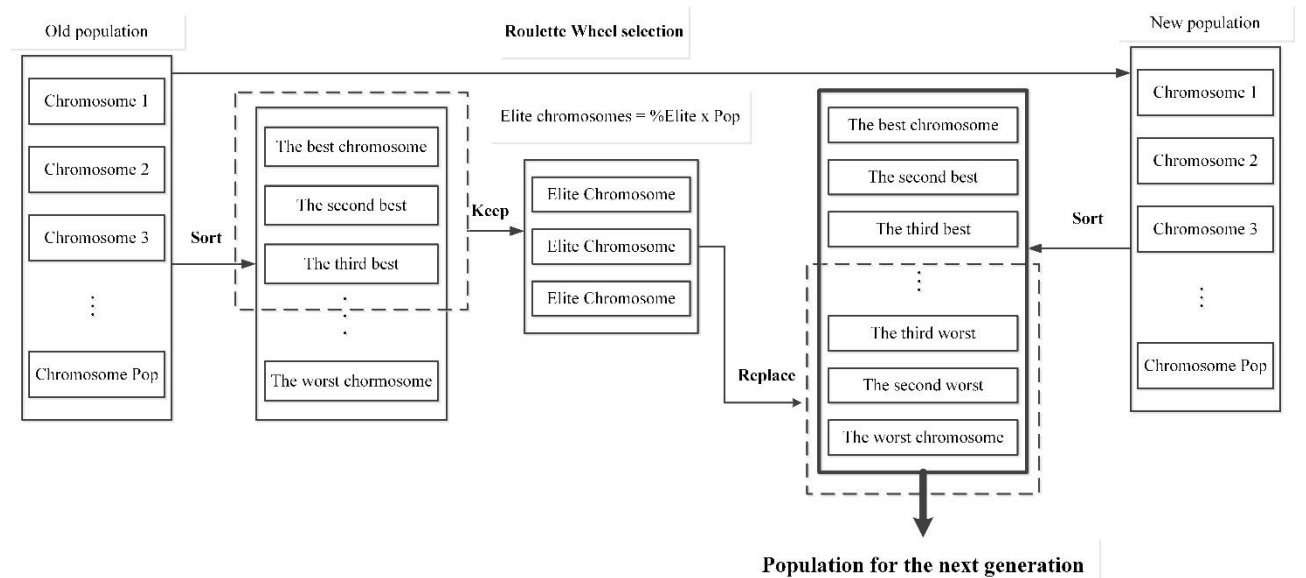


Figure 8 Mechanism for Elitist selection and Roulette wheel selection

xii) choose chromosomes by using roulette wheel selection - the probability of selecting an individual is proportional to its relative fitness. The roulette wheel is 'spun' repeatedly to

produce a new population of the same size as the initial population. Then, the chromosomes in the new population are sorted in accordance with their fitness. The least fit chromosomes are replaced with elite chromosomes;

- xiii) the GA process is terminated after the specified number of generations and the best-so-far solution is reported and shown as a graphic.

The selection of GA parameters (population size, number of generations and the probabilities of crossover and mutation) has a large impact on their performance (Pongcharoen et al. 2007). The appropriate settings of the GA parameters for the machine layout problems was considered by Vitayasak (2011), in which an analysis of variance (ANOVA) suggested that the probability of crossover ( $P_c$ ) and mutation ( $P_m$ ) should be set at 0.9 and 0.5, respectively, with 50 chromosomes and 50 generations. The genetic operators adopted in this work were Two-point Centre Crossover (2PCX) and Two Operation Random Swap (2ORS) (Vitayasak & Pongcharoen, 2011). The GA based layout design tool was developed and coded in a modular style using the Tool Command Language and Tool Kit (Tcl/Tk) programming language (Ousterhout, 2010).

#### 4. Experimental design and analysis

The computational experiments were conducted using eleven datasets (Vitayasak & Pongcharoen, 2018), which had different numbers of non-identical machines, with various product types as shown in Table 2. Each type of product had different demand profiles and machine sequences, as shown in Table 3. Demand profiles can be uploaded into the program using either empirical data or by selecting a probability distribution (exponential, normal distribution, or uniform). The user can select the number of time periods. In the computational experiments ten time-periods were considered. The layout design approach was based on ‘robust design’, without machine relocation. The experiments were conducted on a personal computer with an Intel Core i5 2.8 GHz CPU and 4 GB DDR3 RAM.

Table 2 Datasets

| Datasets | Number of machines (M) | Number of products (N) |
|----------|------------------------|------------------------|
| 10M5N    | 10                     | 5                      |
| 10M10N   | 10                     | 10                     |
| 20M10N   | 20                     | 10                     |
| 20M20N   | 20                     | 20                     |
| 20M40N   | 20                     | 40                     |
| 30M15N   | 30                     | 15                     |
| 30M30N   | 30                     | 30                     |
| 40M20N   | 40                     | 20                     |
| 40M40N   | 40                     | 40                     |
| 50M25N   | 50                     | 25                     |
| 50M40N   | 50                     | 40                     |

Table 3 Summary of product demand distributions and machine sequences for 10M5N

| Product | Product demand distribution | Machine sequence |
|---------|-----------------------------|------------------|
| 1       | Uniform (100, 200)          | 2-1-6-5-8-9-3-4  |
| 2       | Uniform (50, 100)           | 10-8-7-5-9-6-1   |
| 3       | Normal (180, 50)            | 9-2-7-4          |
| 4       | Normal (300, 120)           | 8-10-5-9-6       |
| 5       | Exponential (1/200)         | 2-4-8-10-7       |

To investigate the effect of number of unavailable machines on material flow distance, the following three maintenance scenarios were considered: Scenario I: only preventive maintenance (PM); Scenario II: only corrective maintenance (CM); and Scenario III: both PM and CM.

For scenario I, the ratio of the number of machines with period-based PM to the number with production quantity-based PM (PPM/QPM) in each period were studied at three levels, 20/80,

50/50, and 80/20. For scenario II, the percentage of machines with corrective maintenance (%CM) was also considered at three levels, 10%, 20% and 30%. For scenario III, two levels of PPM/QPM ratio (20/80 and 80/20) and two levels of %CM (10% and 30%) were studied. During periods of maintenance alternative machines were used, which required changes to the routings.

Each experiment was replicated thirty times using different random seeds with a full factorial design. There were eleven datasets, thirty replications, three levels of the PPM/QPM ratio, and three levels of %CM, which gave a total of  $11 \times 30 \times 3 = 990$  runs for scenario I and II. In scenario III, two levels of PPM/QPM ratio and two levels of %CM were studied with eleven datasets, and thirty replications, so the total number of computational runs was  $2 \times 2 \times 11 \times 30 = 1,320$  runs.

The experiments considered robust layout design under dynamic demand and machine maintenance. The objective was to minimise the material flow distance ( $MFD^*$ ). The distance travelled obtained from the layout design without consideration of maintenance was termed  $MFD$ . The  $MFD$  for scenario II was adopted from the previous work (Vitayasak & Pongcharoen, 2015). Both  $MFD^*$  and  $MFD$  were calculated using Eq. (1). The computational results obtained from the robust layout design without and with consideration of machine maintenance are described in the following subsections.

#### 4.1 Layout design without and with consideration of machine maintenance

The material flow distances obtained from two layout design approaches without and with consideration of maintenance ( $MFD$  and  $MFD^*$ ) are shown in Table 4, 5, and 6. When maintenance considerations are not included, the  $MFD$  is determined based on the machine-processing route; whilst when machine maintenance is considered, the  $MFD^*$  is evaluated from the alternative machine-processing route.

The layout design with consideration of maintenance operations (PM, CM or both PM and CM) resulted in shorter travel distance for almost all the datasets.  $MFD^*$  was reduced by up to 30.91% (10M10N dataset, with the 20/80 ratio), 9.8% (40M20N dataset, with 30%CM), and 20.7% (10M10N dataset, with a 20/80 for PM and 30% CM) compared to  $MFD$  for scenarios I, II, III, respectively. The shorter distances were achieved by the design approach that considered alternative machines in the machine-processing routes. However, the  $MFD^*$  based on 50/50 PPM/QPM and 40M40N datasets in scenario I were longer due to the use of alternative machines and their location. The experimental results and differences in  $MFD$  and  $MFD^*$  for each scenario were analysed statistically (discussed in section 4.2).

The PPM/QPM ratios in scenario I, % CM in scenario II, and both PPM/QPM ratio and %CM in scenario III effected both  $MFD$  and  $MFD^*$ . Changes in the flow distances had no obvious patterns for example, the proportion of PPM in PPM/QPM ratios resulted in shorter distances (both  $MFD$  and  $MFD^*$ ) in 10M5N dataset, whilst the  $MFD^*$  increased in the 10M10N, 20M10N, 20M20N, 20M40N, and 30M15N datasets. In scenario II, a number of machines in CM increased but the distance varied, in some cases shorter, in other cases longer. These results show that production conditions can make the layout more or less efficient.

The graphical layouts produced by the program with and without maintenance consideration are shown in Figure 9a) and Figure 9b), respectively, both figures are the machine arrangements produced by one replication of the 40M20N dataset in the 10%CM case from scenario II. In period 10, 2-3 (MC2-MC3) is part of the machine sequence for product no.12. In Figure 9a) machine 3 is unavailable because of CM, and machine 31 (MC31) is the alternative machine. The sequence was changed to 2-31 (MC2-MC31). The flow distance between MC2 and MC31 in Figure 9a) is shorter than in Figure 9b) due to the layout design.

Table 4 Comparison of MFD and MFD\* for scenario I: PM

| Dataset | Value | MFD based on PPM/QPM (metre) |                     |               | MFD* based on PPM/QPM (metre) |                      |                      |
|---------|-------|------------------------------|---------------------|---------------|-------------------------------|----------------------|----------------------|
|         |       | 20/80                        | 50/50               | 80/20         | 20/80                         | 50/50                | 80/20                |
| 10M5N   | Mean  | 732,542.5                    | 682,908.9           | 671,328.9     | <b>691,865.7</b>              | <b>668,652.3</b>     | <b>665,583.0</b>     |
|         | SD    | 24,647.6                     | 20,695.9            | 20,238.0      | 4,119.6                       | 11,341.9             | 13,758.9             |
|         | Min   | 713,598.0                    | 664,472.9           | 654,634.8     | 689,136.2                     | 661,275.3            | 654,634.8            |
|         | Max   | 832,939.7                    | 736,192.5           | 722,275.7     | 705,477.0                     | 702,680.3            | 700,175.2            |
| 10M10N  | Mean  | 1,976,667.4                  | 1,892,978.1         | 1,859,314.2   | <b>1,365,585.7</b>            | <b>1,555,505.8</b>   | <b>1,713,101.3</b>   |
|         | SD    | 49,187.6                     | 16,297.4            | 20,541.5      | 30,343.5                      | 18,713.4             | 14,422.8             |
|         | Min   | 1,861,464.9                  | 1,873,784.0         | 1,810,030.5   | 1,332,408.9                   | 1,539,135.7          | 1,700,812.0          |
|         | Max   | 2,016,763.9                  | 1,932,690.0         | 1,881,312.6   | 1,455,138.8                   | 1,635,094.6          | 1,742,679.4          |
| 20M10N  | Mean  | 4,001,771.7                  | 3,940,840.1         | 3,729,899.9   | <b>3,592,326.6</b>            | <b>3,634,375.6</b>   | <b>3,614,821.5</b>   |
|         | SD    | 78,242.4                     | 79,494.8            | 68,393.4      | 73,249.1                      | 43,154.5             | 44,409.6             |
|         | Min   | 3,829,033.9                  | 3,821,550.9         | 3,599,206.3   | 3,465,857.2                   | 3,539,722.1          | 3,539,102.4          |
|         | Max   | 4,101,750.6                  | 4,085,982.0         | 3,842,643.8   | 3,766,232.0                   | 3,722,638.0          | 3,727,000.0          |
| 20M20N  | Mean  | 11,513,726.3                 | 10,783,205.5        | 10,843,729.9  | <b>9,977,229.7</b>            | <b>10,189,105.8</b>  | <b>10,627,060.1</b>  |
|         | SD    | 299,771.8                    | 298,390.9           | 240,696.3     | 244,037.1                     | 121,587.8            | 115,279.7            |
|         | Min   | 11,071,694.1                 | 10,333,942.9        | 10,463,019.1  | 9,597,502.4                   | 9,989,522.6          | 10,432,751.3         |
|         | Max   | 12,130,858.2                 | 11,517,033.3        | 11,454,630.8  | 10,524,709.4                  | 10,486,443.6         | 10,862,024.5         |
| 20M40N  | Mean  | 21,401,460.7                 | 19,986,017.0        | 20,544,511.3  | <b>18,412,155.3</b>           | <b>18,938,010.2</b>  | <b>19,970,511.5</b>  |
|         | SD    | 512,797.8                    | 578,927.0           | 323,605.9     | 391,668.2                     | 230,848.5            | 232,269.3            |
|         | Min   | 20,603,137.2                 | 18,731,438.0        | 19,999,276.1  | 17,817,505.4                  | 18,475,407.8         | 19,590,558.5         |
|         | Max   | 22,339,703.9                 | 21,082,385.4        | 21,104,899.6  | 19,093,318.0                  | 19,437,762.3         | 20,595,303.8         |
| 30M15N  | Mean  | 8,789,956.5                  | 8,551,413.8         | 8,643,304.4   | <b>7,956,149.15</b>           | <b>8,440,682.20</b>  | <b>8,483,438.64</b>  |
|         | SD    | 163,832.5                    | 191,461.6           | 173,280.2     | 194,371.04                    | 131,806.11           | 87,145.06            |
|         | Min   | 8,515,022.2                  | 8,255,329.1         | 8,206,987.7   | 7,466,729.75                  | 8,179,130.67         | 8,328,513.24         |
|         | Max   | 9,175,074.3                  | 8,926,977.0         | 8,949,400.7   | 8,438,340.21                  | 8,715,695.05         | 8,701,946.22         |
| 30M30N  | Mean  | 19,301,863.60                | 18,487,734.83       | 18,690,797.41 | <b>17,204,962.04</b>          | <b>17,396,236.45</b> | <b>18,214,404.94</b> |
|         | SD    | 435,923.13                   | 516,278.59          | 380,761.66    | 402,715.31                    | 353,777.78           | 263,081.10           |
|         | Min   | 18,372,318.53                | 17,551,378.72       | 17,995,914.35 | 16,445,449.33                 | 16,716,437.07        | 17,375,926.59        |
|         | Max   | 20,179,254.75                | 19,818,815.62       | 19,456,224.74 | 18,125,773.31                 | 18,031,117.12        | 18,725,122.02        |
| 40M20N  | Mean  | 18,858,370.7                 | 17,337,722.43       | 17,809,046.9  | <b>17,318,043.57</b>          | <b>17,225,214.19</b> | <b>17,255,004.23</b> |
|         | SD    | 511,956.3                    | 447,197.64          | 488,921.8     | 296,621.80                    | 365,120.69           | 378,466.45           |
|         | Min   | 17,894,054.6                 | 16,480,907.34       | 16,853,058.9  | 16,508,074.48                 | 16,539,613.57        | 16,600,313.04        |
|         | Max   | 20,246,679.0                 | 18,345,406.56       | 18,957,250.8  | 17,975,588.85                 | 17,916,696.26        | 18,277,513.32        |
| 40M40N  | Mean  | 32,803,402.4                 | <b>30,982,086.8</b> | 31,641,802.8  | <b>31,298,488.0</b>           | 31,035,390.7         | <b>31,345,619.6</b>  |
|         | SD    | 801,659.0                    | 722,317.8           | 650,073.4     | 726,381.7                     | 711,805.7            | 620,078.0            |
|         | Min   | 30,977,346.9                 | 29,219,342.9        | 30,194,195.0  | 30,232,613.4                  | 29,534,475.2         | 30,301,396.8         |
|         | Max   | 34,205,187.1                 | 32,381,014.5        | 32,864,760.4  | 32,875,952.8                  | 32,327,958.4         | 32,969,441.4         |
| 50M25N  | Mean  | 30,416,821.5                 | 28,333,573.0        | 29,107,471.2  | <b>29,229,012.2</b>           | <b>28,160,455.8</b>  | <b>28,469,378.4</b>  |
|         | SD    | 760,184.5                    | 633,765.3           | 650,899.3     | 594,235.6                     | 493,595.3            | 595,960.7            |
|         | Min   | 28,813,572.1                 | 26,841,331.4        | 27,568,289.9  | 28,053,520.0                  | 27,109,933.9         | 27,433,665.5         |
|         | Max   | 31,820,838.4                 | 29,787,280.8        | 30,314,566.6  | 30,417,033.0                  | 29,194,486.7         | 29,549,430.7         |
| 50M40N  | Mean  | 43,031,913.11                | 40,691,396.66       | 41,268,975.91 | <b>40,460,200.71</b>          | <b>39,490,367.57</b> | <b>40,344,555.51</b> |
|         | SD    | 952,627.77                   | 918,014.12          | 879,344.63    | 972,265.88                    | 592,128.02           | 751,780.72           |
|         | Min   | 40,965,451.37                | 38,282,898.46       | 39,139,888.29 | 39,055,623.37                 | 38,466,880.56        | 38,826,428.61        |
|         | Max   | 45,404,975.41                | 42,428,452.96       | 43,581,746.30 | 44,343,340.20                 | 40,718,144.44        | 42,392,739.34        |

Table 5 Comparison of MFD and MFD\* for scenario II: CM

| Dataset | Value | MFD based on %CM (metre) |              |              | MFD* based on %CM (metre) |                      |                      |
|---------|-------|--------------------------|--------------|--------------|---------------------------|----------------------|----------------------|
|         |       | 10                       | 20           | 30           | 10                        | 20                   | 30                   |
| 10M5N   | Mean  | 595,992.6                | 648,008.0    | 718,537.9    | <b>590,735.3</b>          | <b>635,137.6</b>     | <b>654,871.8</b>     |
|         | SD    | 18,962.6                 | 22,179.8     | 19,694.1     | 16,296.5                  | 12,580.0             | 4,934.4              |
|         | Min   | 578,595.5                | 629,746.0    | 703,029.4    | 578,595.5                 | 626,338.8            | 650,562.2            |
|         | Max   | 649,594.9                | 701,533.4    | 774,072.3    | 625,753.0                 | 673,371.0            | 668,980.6            |
| 10M10N  | Mean  | 1,743,496.2              | 1,820,137.3  | 1,900,532.4  | <b>1,714,028.2</b>        | <b>1,768,381.9</b>   | <b>1,743,789.8</b>   |
|         | SD    | 23,439.5                 | 13,037.3     | 25,364.2     | 14,977.4                  | 6,627.3              | 5,350.4              |
|         | Min   | 1,724,716.2              | 1,798,904.2  | 1,831,347.7  | 1,705,903.0               | 1,762,266.7          | 1,732,380.9          |
|         | Max   | 1,806,196.4              | 1,865,916.6  | 1,918,760.8  | 1,768,640.5               | 1,782,853.8          | 1,759,054.9          |
| 20M10N  | Mean  | 3,542,104.0              | 3,628,745.5  | 3,941,721.4  | <b>3,502,114.8</b>        | <b>3,486,977.2</b>   | <b>3,660,302.0</b>   |
|         | SD    | 70,083.5                 | 90,727.4     | 93,797.2     | 65,178.1                  | 57,637.9             | 53,742.4             |
|         | Min   | 3,405,568.5              | 3,491,732.5  | 3,751,832.7  | 3,374,479.0               | 3,385,945.7          | 3,572,248.2          |
|         | Max   | 3,697,350.4              | 3,825,789.1  | 4,136,080.9  | 3,612,987.2               | 3,590,665.7          | 3,776,400.2          |
| 20M20N  | Mean  | 10,886,407.5             | 11,491,341.5 | 10,040,630.5 | <b>9,975,829.5</b>        | <b>10,271,479.3</b>  | <b>10,775,891.3</b>  |
|         | SD    | 377,961.7                | 379,507.2    | 64,521.2     | 150,438.9                 | 136,099.6            | 122,597.3            |
|         | Min   | 10,135,672.5             | 10,873,095.3 | 9,911,473.3  | 9,634,447.2               | 9,986,824.9          | 10,549,215.6         |
|         | Max   | 11,917,048.8             | 12,629,320.2 | 10,145,030.9 | 10,164,784.6              | 10,494,467.5         | 11,066,485.3         |
| 20M40N  | Mean  | 20,347,121.1             | 21,261,068.2 | 20,815,688.1 | <b>20,055,976.8</b>       | <b>20,538,439.4</b>  | <b>19,792,882.4</b>  |
|         | SD    | 318,814.4                | 355,670.7    | 361,285.2    | 256,549.6                 | 255,692.7            | 244,704.3            |
|         | Min   | 19,887,820.5             | 20,614,947.8 | 20,049,924.7 | 19,521,965.0              | 19,990,144.4         | 19,385,382.5         |
|         | Max   | 21,181,869.2             | 22,179,471.9 | 21,493,810.5 | 20,638,112.7              | 21,214,033.3         | 20,368,678.3         |
| 30M15N  | Mean  | 8,276,170.0              | 8,489,326.7  | 9,056,617.6  | <b>8,112,260.89</b>       | <b>8,109,334.22</b>  | <b>8,517,554.15</b>  |
|         | SD    | 213,714.2                | 209,076.6    | 197,351.2    | 160,677.68                | 136,576.21           | 122,294.57           |
|         | Min   | 7,915,148.6              | 8,041,397.4  | 8,663,135.8  | 7,716,345.63              | 7,912,373.96         | 8,342,702.04         |
|         | Max   | 8,642,410.7              | 8,884,425.3  | 9,448,623.8  | 8,369,170.86              | 8,407,071.29         | 8,866,532.80         |
| 30M30N  | Mean  | 18,488,449.3             | 19,213,555.9 | 19,924,934.3 | <b>18,056,501.0</b>       | <b>18,570,871.1</b>  | <b>18,870,939.7</b>  |
|         | SD    | 345,013.1                | 376,796.3    | 390,559.1    | 290,811.3                 | 257,302.4            | 425,340.4            |
|         | Min   | 17,813,400.0             | 18,531,809.7 | 19,075,102.0 | 17,529,610.1              | 18,153,692.7         | 18,285,164.3         |
|         | Max   | 19,047,688.1             | 19,999,742.7 | 20,852,219.5 | 18,538,341.9              | 19,296,918.2         | 19,878,511.9         |
| 40M20N  | Mean  | 17,166,328.0             | 17,680,469.6 | 19,807,215.4 | <b>16,963,181.88</b>      | <b>16,918,410.83</b> | <b>17,865,200.18</b> |
|         | SD    | 596,320.1                | 711,828.6    | 628,823.9    | 450,898.81                | 386,285.35           | 427,203.26           |
|         | Min   | 16,275,826.0             | 16,382,959.9 | 18,444,970.6 | 16,003,309.77             | 16,191,351.68        | 16,949,237.51        |
|         | Max   | 18,793,575.0             | 19,249,222.1 | 20,954,182.8 | 17,939,692.95             | 17,785,665.63        | 18,571,965.60        |
| 40M40N  | Mean  | 30,354,735.4             | 32,107,292.1 | 34,014,129.5 | <b>30,014,644.7</b>       | <b>31,471,994.4</b>  | <b>31,977,370.8</b>  |
|         | SD    | 710,209.0                | 732,868.0    | 913,114.6    | 688,480.4                 | 724,316.4            | 496,761.8            |
|         | Min   | 28,861,378.3             | 30,625,120.7 | 32,160,002.9 | 28,700,335.2              | 30,208,296.0         | 30,629,629.6         |
|         | Max   | 31,531,345.4             | 33,591,573.4 | 36,340,903.2 | 31,406,586.2              | 32,832,899.7         | 32,865,393.8         |
| 50M25N  | Mean  | 27,178,003.2             | 30,270,244.4 | 30,870,860.1 | <b>27,092,641.4</b>       | <b>29,081,579.6</b>  | <b>28,831,111.7</b>  |
|         | SD    | 668,805.8                | 1,470,163.5  | 1,062,502.1  | 568,595.4                 | 572,029.1            | 635,753.7            |
|         | Min   | 25,890,014.3             | 28,608,583.1 | 29,248,548.6 | 25,769,239.5              | 27,571,531.5         | 27,526,568.9         |
|         | Max   | 28,643,707.9             | 34,650,791.3 | 33,655,833.1 | 28,551,539.0              | 29,899,271.5         | 30,363,093.6         |
| 50M40N  | Mean  | 38,665,200.8             | 40,623,452.1 | 42,813,257.3 | <b>38,410,673.5</b>       | <b>39,068,770.5</b>  | <b>39,716,291.9</b>  |
|         | SD    | 926,397.9                | 875,337.7    | 1,029,425.4  | 996,253.1                 | 579,898.0            | 1,572,021.9          |
|         | Min   | 36,759,326.4             | 38,525,081.4 | 40,711,956.5 | 36,490,243.4              | 37,972,072.9         | 35,925,018.8         |
|         | Max   | 40,206,702.1             | 42,427,400.6 | 45,364,718.2 | 41,594,068.6              | 39,965,774.8         | 41,252,991.8         |

Table 6 Comparison of MFD and MFD\* for scenario III: PM and CM

| Dataset | Value | MFD based on PPM/QPM (metre) |              |                 |              | MFD* based on PPM/QPM (metre) |                     |                     |                     |
|---------|-------|------------------------------|--------------|-----------------|--------------|-------------------------------|---------------------|---------------------|---------------------|
|         |       | 20/80 with %CM:              |              | 80/20 with %CM: |              | 20/80 with %CM:               |                     | 80/20 with %CM:     |                     |
|         |       | 10                           | 30           | 10              | 30           | 10                            | 30                  | 10                  | 30                  |
| 10M5N   | Mean  | 756,154.2                    | 759,314.1    | 711,630.5       | 774,386.9    | <b>696,449.1</b>              | <b>682,969.7</b>    | <b>689,155.4</b>    | <b>690,297.0</b>    |
|         | SD    | 13,883.2                     | 19,098.0     | 16,444.3        | 19,695.7     | 2,988.0                       | 7,388.5             | 3,499.3             | 6,947.8             |
|         | Min   | 740,685.2                    | 748,179.5    | 701,040.9       | 752,025.0    | 692,655.0                     | 679,476.9           | 687,224.1           | 685,348.6           |
|         | Max   | 820,830.6                    | 822,493.2    | 757,159.5       | 820,557.4    | 704,306.4                     | 716,359.4           | 705,154.0           | 707,057.2           |
| 10M10N  | Mean  | 1,696,411.2                  | 1,625,937.8  | 1,919,182.4     | 2,003,574.7  | <b>1,363,107.2</b>            | <b>1,299,582.2</b>  | <b>1,696,411.2</b>  | <b>1,625,937.8</b>  |
|         | SD    | 12,532.6                     | 22,534.9     | 28,228.1        | 29,694.8     | 24,383.2                      | 17,638.0            | 12,532.6            | 22,534.9            |
|         | Min   | 1,676,742.0                  | 1,613,265.3  | 1,863,424.6     | 1,930,963.5  | 1,340,688.4                   | 1,281,094.1         | 1,676,742.0         | 1,613,265.3         |
|         | Max   | 1,718,454.6                  | 1,669,606.3  | 1,964,517.5     | 2,051,139.6  | 1,420,904.3                   | 1,342,070.7         | 1,718,454.6         | 1,669,606.3         |
| 20M10N  | Mean  | 4,119,919.6                  | 4,133,927.1  | 3,908,550.1     | 4,005,296.5  | <b>3,595,637.1</b>            | <b>3,567,280.8</b>  | <b>3,750,587.2</b>  | <b>3,667,979.3</b>  |
|         | SD    | 95,199.3                     | 98,473.9     | 82,028.7        | 94,047.0     | 62,974.0                      | 84,852.4            | 53,481.9            | 65,916.9            |
|         | Min   | 3,890,903.3                  | 3,963,443.5  | 3,679,723.0     | 3,826,392.1  | 3,465,971.8                   | 3,409,105.7         | 3,652,461.3         | 3,575,148.0         |
|         | Max   | 4,279,254.9                  | 4,285,285.7  | 4,060,176.6     | 4,158,645.2  | 3,733,667.8                   | 3,780,967.2         | 3,889,113.3         | 3,834,580.3         |
| 20M20N  | Mean  | 11,684,238.3                 | 11,587,409.5 | 11,436,897.2    | 11,632,622.8 | <b>9,784,872.0</b>            | <b>9,704,728.0</b>  | <b>10,640,238.3</b> | <b>10,580,494.1</b> |
|         | SD    | 567,227.3                    | 393,346.9    | 266,980.2       | 286,861.7    | 229,961.4                     | 249,658.8           | 115,081.6           | 126,464.7           |
|         | Min   | 10,178,930.6                 | 10,836,389.6 | 10,991,330.4    | 11,228,632.5 | 9,320,756.7                   | 9,240,327.7         | 10,450,294.7        | 10,416,982.1        |
|         | Max   | 12,506,884.6                 | 12,325,671.3 | 12,091,105.6    | 12,338,001.2 | 10,340,840.9                  | 10,161,215.5        | 10,874,935.8        | 10,968,645.8        |
| 20M40N  | Mean  | 21,547,184.5                 | 21,955,526.9 | 20,961,451.7    | 21,383,550.2 | <b>18,351,926.2</b>           | <b>17,952,853.6</b> | <b>19,647,857.8</b> | <b>19,339,586.6</b> |
|         | SD    | 586,510.4                    | 651,830.5    | 351,224.6       | 468,077.5    | 395,256.3                     | 373,085.4           | 181,672.6           | 251,284.2           |
|         | Min   | 20,404,044.1                 | 20,898,599.4 | 20,347,095.3    | 20,491,165.3 | 17,365,794.3                  | 17,373,888.9        | 19,201,604.1        | 18,873,281.5        |
|         | Max   | 22,693,245.3                 | 23,264,730.7 | 21,503,352.5    | 22,172,473.9 | 19,154,074.6                  | 18,846,545.3        | 20,013,134.3        | 19,854,377.1        |
| 30M15N  | Mean  | 9,103,269.9                  | 9,233,038.8  | 8,896,745.1     | 8,987,536.6  | <b>8,267,592.0</b>            | <b>8,021,975.1</b>  | <b>8,529,552.3</b>  | <b>8,552,366.8</b>  |
|         | SD    | 169,537.0                    | 171,008.2    | 173,206.4       | 184,264.6    | 140,270.5                     | 148,486.1           | 140,431.2           | 135,258.0           |
|         | Min   | 8,819,073.4                  | 8,963,978.0  | 8,549,216.6     | 8,468,788.2  | 8,060,902.7                   | 7,728,910.4         | 8,317,774.1         | 8,266,294.8         |
|         | Max   | 9,527,748.8                  | 9,604,435.3  | 9,173,632.1     | 9,222,950.2  | 8,588,666.9                   | 8,360,262.2         | 8,775,369.8         | 8,856,695.1         |
| 30M30N  | Mean  | 19,505,928.3                 | 19,762,956.4 | 19,601,415.9    | 19,428,292.6 | <b>16,932,208.1</b>           | <b>17,363,912.1</b> | <b>18,923,550.0</b> | <b>18,520,402.3</b> |
|         | SD    | 505,868.8                    | 572,729.5    | 370,660.4       | 397,525.0    | 280,582.2                     | 415,910.7           | 319,813.1           | 323,064.5           |
|         | Min   | 18,482,344.2                 | 18,796,062.8 | 18,983,931.9    | 18,701,559.1 | 16,253,491.5                  | 16,561,240.6        | 18,243,241.7        | 17,880,132.1        |
|         | Max   | 20,720,940.2                 | 20,737,246.1 | 20,303,728.3    | 20,185,673.3 | 17,436,314.9                  | 18,564,151.2        | 19,483,474.2        | 19,100,631.7        |
| 40M20N  | Mean  | 20,088,567.2                 | 20,622,426.6 | 19,320,811.0    | 19,820,034.4 | <b>17,871,005.5</b>           | <b>18,206,122.4</b> | <b>18,052,155.3</b> | <b>17,931,324.5</b> |
|         | SD    | 668,154.1                    | 641,100.3    | 506,074.1       | 611,456.3    | 341,064.0                     | 373,018.9           | 424,514.7           | 380,688.6           |
|         | Min   | 18,925,914.0                 | 19,444,805.3 | 18,085,390.0    | 18,444,970.6 | 17,206,286.8                  | 17,639,624.0        | 17,442,744.0        | 17,317,107.6        |
|         | Max   | 21,436,825.7                 | 21,962,994.3 | 20,085,304.0    | 20,954,182.8 | 18,476,883.6                  | 19,025,693.3        | 19,313,919.9        | 18,744,777.1        |
| 40M40N  | Mean  | 34,524,264.6                 | 35,205,647.0 | 34,234,719.4    | 34,661,170.4 | <b>32,227,970.6</b>           | <b>32,019,455.4</b> | <b>32,683,300.5</b> | <b>32,504,726.6</b> |
|         | SD    | 944,627.4                    | 933,575.1    | 865,431.9       | 857,340.2    | 840,403.8                     | 679,697.4           | 617,009.5           | 597,281.1           |
|         | Min   | 32,200,672.3                 | 33,130,117.1 | 32,262,815.8    | 32,259,884.6 | 30,986,173.3                  | 30,810,745.5        | 31,501,492.7        | 31,074,336.7        |
|         | Max   | 35,961,923.5                 | 36,710,861.5 | 36,393,348.9    | 36,193,284.5 | 34,097,699.1                  | 33,571,654.4        | 34,434,440.4        | 33,529,452.6        |
| 50M25N  | Mean  | 32,774,478.7                 | 32,651,407.2 | 30,839,771.0    | 31,046,583.7 | <b>30,023,350.7</b>           | <b>29,835,449.8</b> | <b>29,922,703.3</b> | <b>29,095,235.1</b> |
|         | SD    | 834,599.6                    | 877,062.3    | 621,845.2       | 784,307.3    | 531,123.2                     | 462,479.7           | 1,606,028.9         | 536,007.8           |
|         | Min   | 31,354,594.9                 | 31,028,567.0 | 29,245,455.1    | 29,411,674.2 | 28,816,579.1                  | 28,708,173.9        | 28,455,958.5        | 27,843,837.0        |
|         | Max   | 34,948,695.9                 | 34,827,671.8 | 31,739,507.5    | 32,347,650.6 | 31,014,303.3                  | 30,671,972.6        | 34,676,639.3        | 30,338,961.7        |
| 50M40N  | Mean  | 44,086,719.7                 | 44,636,696.3 | 43,086,633.8    | 43,174,077.6 | <b>41,169,524.8</b>           | <b>41,188,981.3</b> | <b>41,030,026.2</b> | <b>40,977,432.1</b> |
|         | SD    | 994,298.1                    | 1,021,741.6  | 1,044,123.1     | 1,042,832.8  | 684,203.7                     | 760,165.2           | 855,671.1           | 840,875.4           |
|         | Min   | 41,722,477.5                 | 42,411,002.7 | 40,555,375.7    | 40,054,726.3 | 39,994,590.8                  | 39,816,605.2        | 39,447,020.7        | 39,780,973.9        |
|         | Max   | 46,434,531.2                 | 47,486,809.8 | 45,290,685.9    | 45,435,725.5 | 42,636,809.1                  | 42,899,341.2        | 42,546,100.7        | 43,250,507.1        |



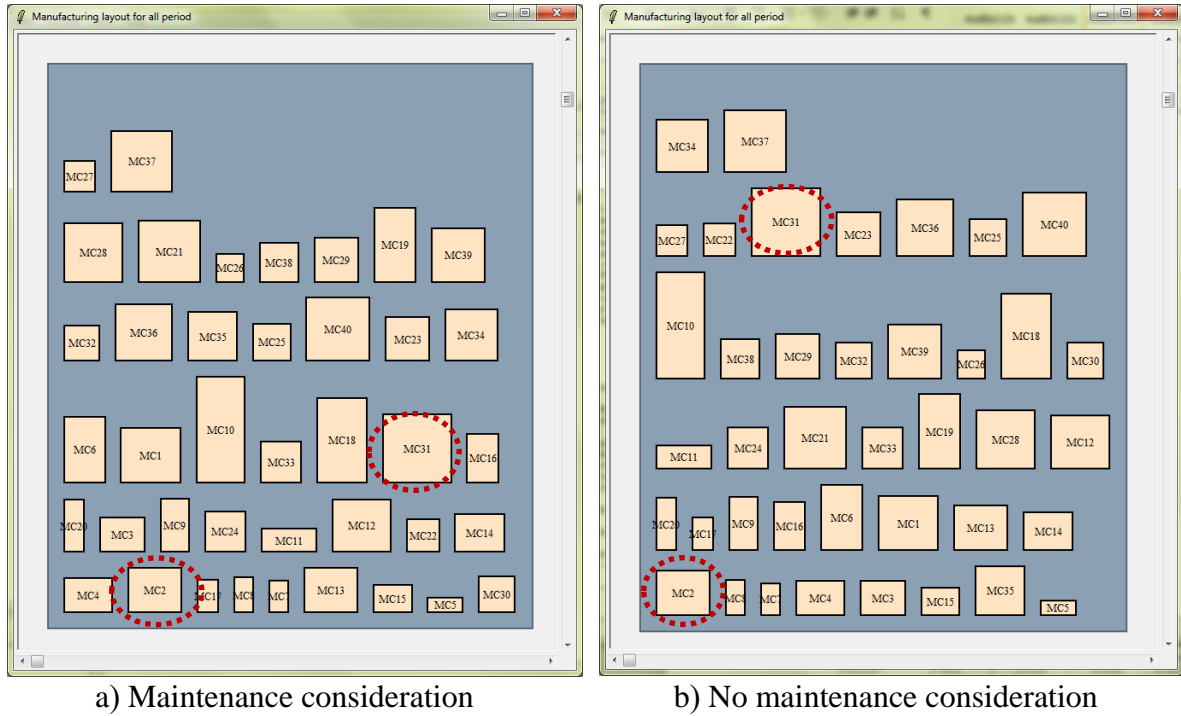


Figure 9 Graphical layout for robust design for 40M20N dataset in 10%CM for scenario II

## 4.2 Statistical analysis on the experimental results

The experimental results in Table 4, 5, and 6 were analysed using the Student's *t*-test and analysis of variance (ANOVA).

### 4.2.1 The Student's *t*-test

The Student's *t*-test was used to test differences in the means *MFD* and *MFD\** for the three scenarios shown in Table 7. For scenario I, there were statistically significant differences ( $P$ -value  $< 0.05$ ) with a 95% confidence interval, except for the 50/50 PPM/QPM ratio for problems 40M20N and 40M40N, and the 80/20 PPM/QPM ratio for the 40M40N problem. For scenario II, there were statistically significant differences in the means of *MFD* and *MFD\** except for 10%CM for the 10M5N, 40M20N 40M40N and 50M40N problems. For scenario III, the  $P$ -values were less than 0.05 for all datasets, so there were statistically significant differences in the mean of *MFD* and *MFD\**. These results emphasised that effective layout design cannot overlook machine maintenance.

Table 7  $P$  values for *t*-test for scenario I, II, and III

| Dataset | scenario I<br>PPM/QPM: |       |       | scenario II<br>%CM |       |       | scenario III    |       |                 |       |
|---------|------------------------|-------|-------|--------------------|-------|-------|-----------------|-------|-----------------|-------|
|         |                        |       |       |                    |       |       | 20/80 with %CM: |       | 80/20 with %CM: |       |
|         | 20/80                  | 50/50 | 80/20 | 10                 | 20    | 30    | 10              | 30    | 10              | 30    |
| 10M5N   | 0.000                  | 0.000 | 0.000 | 0.254              | 0.008 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 10M10N  | 0.000                  | 0.000 | 0.000 | 0.000              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 20M10N  | 0.000                  | 0.000 | 0.000 | 0.026              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 20M20N  | 0.000                  | 0.000 | 0.000 | 0.000              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 20M40N  | 0.000                  | 0.000 | 0.000 | 0.000              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 30M15N  | 0.000                  | 0.000 | 0.000 | 0.001              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 30M30N  | 0.000                  | 0.000 | 0.000 | 0.000              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 40M20N  | 0.000                  | 0.290 | 0.000 | 0.143              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 40M40N  | 0.000                  | 0.774 | 0.076 | 0.065              | 0.001 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 50M25N  | 0.020                  | 0.000 | 0.000 | 0.020              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |
| 50M40N  | 0.000                  | 0.000 | 0.000 | 0.310              | 0.000 | 0.000 | 0.000           | 0.000 | 0.000           | 0.000 |

#### 4.2.2 Analysis of variance (ANOVA)

The effects of PPM/QPM ratios in scenario I, the percentages of CM in scenario II (%CM), and both PPM/QPM ratios and %CM in scenario III on material flow distance were analysed using an ANOVA to calculate  $P$  values as shown in Table 8. For scenario I, the results showed that The PPM/QPM ratios significantly affected the material flow distance with a 95% confidence interval, since the  $P$  values are less than 0.05 except for 40M20N and 40M40N. The results suggest that the number of machines with each type of PM had an effect on the flow distance. For scenario II, %CM significantly affected the material flow distance. An increase in the number of CM machines caused more changes in machine sequences, so  $MFD$  increased. However, the machine sequences depended upon the alternative machines defined. For scenario III, the PPM/QPM ratios, %CM, and their interaction were significant factors with a 95% confidence interval for almost all datasets. The influence of the number of machines receiving maintenance machines on material flow distance confirms that maintenance scenario should be recognised in the layout design.

Table 8  $P$  values of ANOVA for scenario I, II, and III

| Dataset | scenario I | scenario II | scenario III |       |               |
|---------|------------|-------------|--------------|-------|---------------|
|         | PPM/QPM    | %CM         | PPM/QPM      | %CM   | PPM/QPM * %CM |
| 10M5N   | 0.000      | 0.000       | 0.000        | 0.000 | 0.000         |
| 10M10N  | 0.016      | 0.000       | 0.000        | 0.000 | 0.339         |
| 20M10N  | 0.000      | 0.000       | 0.000        | 0.000 | 0.000         |
| 20M20N  | 0.000      | 0.000       | 0.000        | 0.000 | 0.000         |
| 20M40N  | 0.000      | 0.000       | 0.000        | 0.000 | 0.000         |
| 30M15N  | 0.000      | 0.000       | 0.000        | 0.000 | 0.000         |
| 30M30N  | 0.000      | 0.000       | 0.000        | 0.818 | 0.000         |
| 40M20N  | 0.808      | 0.000       | 0.717        | 0.000 | 0.000         |
| 40M40N  | 0.176      | 0.000       | 0.000        | 0.001 | 0.000         |
| 50M25N  | 0.000      | 0.000       | 0.000        | 0.079 | 0.000         |
| 50M40M  | 0.000      | 0.000       | 0.225        | 0.909 | 0.803         |

#### 5. Discussions and conclusions

This paper has presented the development of an approach that integrates maintenance planning with the design of non-identical machine layouts subject to dynamic demand, which addresses a gap in the literature. The GA aims to minimise the total material flow distance. The computational experiments were carried out using eleven datasets with different demand distributions. The analysis considered three maintenance scenarios with PPM/QPM (ratios of 20/80, 50/50 and 80/20). Three levels of corrective maintenance were considered 10%, 20% and 30%. A combination of PPM/QPM with ratios of (20/80 and 80/20) and two values of %CM (10% and 30%) were studied. The material flow distances can decrease or increase when some machines were maintained during each period. This was caused by changes in the routings due to the use of alternative machines.

Designing robust machine layouts considering machine maintenance leads to reduced material flow distances up to 30.91%, 9.8%, and 20.7% for PM, CM, and PM and CM scenarios, respectively. The distances obtained from designing the layout without and with maintenance consideration had statistically significant differences in the means. The PPM/QPM ratios, %CM, and a combination of PPM/QPM and %CM had significantly resulted in the material flow distance in almost all datasets.

It can be beneficial for companies to consider both demand and machine uncertainty when designing layouts, providing that the future demand and availability of machines are properly forecast and planned. Further research could consider the option of allowing machines to be rotated by the algorithm.

## 6. Acknowledgement

This work was part of the research project supported by the Thailand Research Fund under grant numbers MRG6080031 and MRG6280168.

## References

- Abedzadeh, M., Mazinani, M., Moradinasab, N., & Roghanian, E. (2013). Parallel variable neighborhood search for solving fuzzy multi-objective dynamic facility layout problem. *International Journal of Advanced Manufacturing Technology*, 65(1-4), 197-211. doi: 10.1007/s00170-012-4160-x
- Altuntas, S., & Selim, H. (2012). Facility layout using weighted association rule-based data mining algorithms: Evaluation with simulation. *Expert Systems with Applications*, 39(1), 3-13. doi: 10.1016/j.eswa.2011.06.045
- Asl, A. D., & Wong, K. Y. (2017). Solving unequal-area static and dynamic facility layout problems using modified particle swarm optimization. *Journal of Intelligent Manufacturing*, 28(6), 1317-1336. doi: 10.1007/s10845-015-1053-5
- Asl, A. D., Wong, K. Y., & Tiwari, M. K. (2016). Unequal-area stochastic facility layout problems: Solutions using improved covariance matrix adaptation evolution strategy, particle swarm optimisation, and genetic algorithm. *International Journal of Production Research*, 54(3), 799-823. doi: 10.1080/00207543.2015.1070217
- Ayodeji, S. P., Adeyeri, M. K., & Ogunsua, A. (2017). Development of dynamic layout model for poundo yam flour processing plant. *Cogent Engineering*, 4(1), 1336872. doi: 10.1080/23311916.2017.1336872
- Azadeh, A., Moghaddam, M., Nazari, T., & Sheikhalishahi, M. (2016). Optimization of facility layout design with ambiguity by an efficient fuzzy multivariate approach. *The International Journal of Advanced Manufacturing Technology*, 84(1-4), 565-579. doi: 10.1007/s00170-015-7714-x
- Azadeh, A., Motevali Haghighi, S., & Asadzadeh, S. M. (2014). A novel algorithm for layout optimization of injection process with random demands and sequence dependent setup times. *Journal of Manufacturing Systems*, 33(2), 287-302. doi: 10.1016/j.jmsy.2013.12.008
- Azadivar, F., & Wang, J. (2000). Facility layout optimization using simulation and genetic algorithms. *International Journal of Production Research*, 38(17 SPEC), 4369-4383.
- Azevedo, M. M., Crispim, J. A., & Pinho de Sousa, J. (2017). A dynamic multi-objective approach for the reconfigurable multi-facility layout problem. *Journal of Manufacturing Systems*, 42, 140-152. doi: 10.1016/j.jmsy.2016.12.008
- Azimi, P., Saberi, E. J. E. C., Studies, E. C., & Research. (2013). An efficient hybrid algorithm for dynamic facility layout problem using simulation technique and PSO. *Economic Computation and Economic Cybernetics Studies and Research*, 47(4).
- Azimi, P., & Soofi, P. (2017). An ANN-based optimization model for facility layout problem using simulation technique. *Scientia Iranica*, 24(1), 364-377.
- Balakrishnan, J. (1992). Solutions for the constrained dynamic facility layout problem. *European Journal of Operational Research*, 57, 280-286.
- Balakrishnan, J., & Cheng, C.-H. (2009). The dynamic plant layout problem: Incorporating rolling horizons and forecast uncertainty. *Omega-International Journal of Management Science*, 37(1), 165-177. doi: 10.1016/j.omega.2006.11.005
- Balakrishnan, J., & Cheng, C. H. (1998). Dynamic layout algorithms: a state-of-the-art survey. *Omega-International Journal of Management Science*, 26(4), 507-521.
- Baykasoglu, A., Dereli, T., & Sabuncu, I. (2006). An Ant Colony Algorithm for solving budget constrained and unconstrained dynamic facility layout problems. *Omega-International Journal of Management Science*, 34(4), 385-396. doi: 10.1016/j.omega.2004.12.001
- Bozorgi, N., Abedzadeh, M., & Zeinali, M. (2015). Tabu search heuristic for efficiency of dynamic facility layout problem. *International Journal of Advanced Manufacturing Technology*, 77(1-4), 689-703. doi: 10.1007/s00170-014-6460-9
- Buzacott, J. A., & Mandelbaum, M. (1985). *Flexibility and productivity in manufacturing systems*. Paper presented at the IE Fall Conference, Chicago.

- Byrne, M. D., & Chutima, P. (1997). Real-time operational control of an FMS with full routing flexibility. *International Journal of Production Economics*, 51(1–2), 109–113. doi: 10.1016/s0925-5273(97)00074-1
- Chae, J., & Regan, A. C. (2016). Layout design problems with heterogeneous area constraints. *Computers & Industrial Engineering*, 102, 198–207. doi: 10.1016/j.cie.2016.10.016
- Chan, W. K., & Malmberg, C. J. (2010). A Monte Carlo simulation based heuristic procedure for solving dynamic line layout problems for facilities using conventional material handling devices. *International Journal of Production Research*, 48(10), 2937–2956. doi: 10.1080/00207540902810536
- Chang, A. Y. (2007). On the measurement of routing flexibility: a multiple attribute approach. *International Journal of Production Economics*, 109(1–2), 122–136. doi: 10.1016/j.ijpe.2006.11.011
- Chang, C. C., Wu, T. H., & Wu, C. W. (2013). An efficient approach to determine cell formation, cell layout and intracellular machine sequence in cellular manufacturing systems. *Computers & Industrial Engineering*, 66(2), 438–450. doi: 10.1016/j.cie.2013.07.009
- Chen, G. Y. (2013). A new data structure of solution representation in hybrid ant colony optimization for large dynamic facility layout problems. *International Journal of Production Economics*, 142(2), 362–371. doi: dx.doi.org/10.1016/j.ijpe.2012.12.012
- Chen, G. Y. H., & Lo, J. C. (2014). Dynamic facility layout with multi-objectives. *Asia-Pacific Journal of Operational Research*, 31(4), 1450027. doi: 10.1142/S0217595914500274
- Cheng Ying, Y., Ab-Samat, H., & Kamaruddin, S. (2016). Practical production layout design for multi-product and small-lot-size production: A case study. *Jurnal Teknologi*, 78(7), 161–175. doi: 10.11113/jt.v78.2893
- Dapa, K., Loreunghup, P., Vitayasak, S., & Pongcharoen, P. (2013). Bat algorithm, genetic algorithm and shuffled frog leaping algorithm for designing machine layout. *Lecture Notes in Computer Science*, 8271, 59–68.
- Dong, M., Wu, C., & Hou, F. (2009). Shortest path based simulated annealing algorithm for dynamic facility layout problem under dynamic business environment. *Expert Systems with Applications*, 36(8), 11221–11232. doi: 10.1016/j.eswa.2009.02.091
- Drira, A., Pierreval, H., & Hajri-Gabouj, S. (2007). Facility layout problems: A survey. *Annual Reviews in Control*, 31(2), 255–267. doi: 10.1016/j.arcontrol.2007.04.001
- Drira, A., Pierreval, H., & Hajri-Gabouj, S. (2013). Design of a robust layout with information uncertainty increasing over time: A fuzzy evolutionary approach. *Engineering Applications of Artificial Intelligence*, 26(3), 1052–1060.
- Dunker, T., Radons, G., & Westkamper, E. (2005). Combining evolutionary computation and dynamic programming for solving a dynamic facility layout problem - Discrete optimization. *European Journal of Operational Research*, 165(1), 55–69.
- Emami, S., & S. Nookabadi, A. (2013). Managing a new multi-objective model for the dynamic facility layout problem. *International Journal of Advanced Manufacturing Technology*, 68(9–12), 2215–2228. doi: 10.1007/s00170-013-4820-5
- Fazlelahi, F. Z., Pournader, M., Gharakhani, M., & Sadjadi, S. J. (2016). A robust approach to design a single facility layout plan in dynamic manufacturing environments using a permutation-based genetic algorithm. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 230(12), 2264–2274. doi: 10.1177/0954405415615728
- Fitouhi, M. C., & Nourelfath, M. (2012). Integrating noncyclical preventive maintenance scheduling and production planning for a single machine. *International Journal of Production Economics*, 136(2), 344–351. doi: 10.1016/j.ijpe.2011.12.021
- Garg, A., & Deshmukh, S. G. (2006). Maintenance management: literature review and directions. *Journal of Quality in Maintenance Engineering*, 12(3), 205–238.
- Ghosh, T., Doloi, B., & Dan, P. K. (2016). Applying soft-computing techniques in solving dynamic multi-objective layout problems in cellular manufacturing system. *International Journal of Advanced Manufacturing Technology*, 86(1–4), 237–257. doi: 10.1007/s00170-015-8070-6
- Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimisation and Machine Learning*. Reading, MA: Addison-Wesley.

- Guan, X., Dai, X., Qiu, B., & Li, J. (2012). A revised electromagnetism-like mechanism for layout design of reconfigurable manufacturing system. *Computers and Industrial Engineering*, 63(1), 98-108. doi: 10.1016/j.cie.2012.01.016
- Hanafy, M., & ElMaraghy, H. (2015). Developing assembly line layout for delayed product differentiation using phylogenetic networks. *International Journal of Production Research*, 53(9), 2633-2651. doi: 10.1080/00207543.2014.974839
- Hicks, C. (2006). A Genetic Algorithm tool for optimising cellular or functional layouts in the capital goods industry. *International Journal of Production Economics*, 104(2), 598-614.
- Holland, J. H. (1962). Outline for a Logical Theory of Adaptive Systems. *Journal of the ACM (JACM)*, 9(3), 297-314. doi: 10.1145/321127.321128
- Hosseini-Nasab, H., & Emami, L. (2013). A hybrid particle swarm optimisation for dynamic facility layout problem. *International Journal of Production Research*, 51(14), 4325-4335. doi: 10.1080/00207543.2013.774486
- Hosseini-Nasab, H., Fereidouni, S., Fatemi Ghomi, S. M. T., & Fakhrazad, M. B. (2018). Classification of facility layout problems: a review study. *International Journal of Advanced Manufacturing Technology*, 94(1-4), 957-977. doi: 10.1007/s00170-017-0895-8
- Hosseini, S., Khaled, A. A., & Vadlamani, S. (2014). Hybrid imperialist competitive algorithm, variable neighborhood search, and simulated annealing for dynamic facility layout problem. *Neural Computing and Applications*, 25(7-8), 1871-1885. doi: 10.1007/s00521-014-1678-x
- Hosseini, S. S., & Seifbarghy, M. (2016). A novel meta-heuristic algorithm for multi-objective dynamic facility layout problem. *RAIRO - Operations Research*, 50(4-5), 869-890. doi: 10.1051/ro/2016057
- Islier, A. A. (1998). A genetic algorithm approach for multiple criteria facility layout design. *International Journal of Production Research*, 36(6), 1549-1569.
- Jithavech, I., & Krishnan, K. K. (2010). A simulation-based approach for risk assessment of facility layout designs under stochastic product demands. *International Journal of Advanced Manufacturing Technology*, 49(1-4), 27-40. doi: 10.1007/s00170-009-2380-5
- Kaveh, M., Dalfard, V. M., & Amiri, S. (2014). A new intelligent algorithm for dynamic facility layout problem in state of fuzzy constraints. *Neural Computing and Applications*, 24(5), 1179-1190. doi: 10.1007/s00521-013-1339-5
- Khaksar-Haghani, F., Kia, R., Mahdavi, I., & Kazemi, M. (2013). A genetic algorithm for solving a multi-floor layout design model of a cellular manufacturing system with alternative process routings and flexible configuration. *International Journal of Advanced Manufacturing Technology*, 66(5-8), 845-865. doi: 10.1007/s00170-012-4370-2
- Kheirkhah, A., Navidi, H., & Messi Bidgoli, M. (2015). Dynamic Facility Layout Problem: A New Bilevel Formulation and Some Metaheuristic Solution Methods. *IEEE Transactions on Engineering Management*, 62(3), 396-410. doi: 10.1109/TEM.2015.2437195
- Kheirkhah, A. S., & Bidgoli, M. M. (2016). Dynamic facility layout problem under competitive environment: a new formulation and some meta-heuristic solution methods. *Production Engineering*, 10(6), 615-632. doi: 10.1007/s11740-016-0703-6
- Kia, R., Baboli, A., Javadian, N., Tavakkoli-Moghaddam, R., Kazemi, M., & Khorrami, J. (2012). Solving a group layout design model of a dynamic cellular manufacturing system with alternative process routings, lot splitting and flexible reconfiguration by simulated annealing. *Computers and Operations Research*, 39(11), 2642-2658. doi: 10.1016/j.cor.2012.01.012
- Kia, R., Javadian, N., Paydar, M. M., & Saidi-Mehrabad, M. (2013). A simulated annealing for intra-cell layout design of dynamic cellular manufacturing systems with route selection, purchasing machines and cell reconfiguration. *Asia-Pacific Journal of Operational Research*, 30(4), 1350004.
- Kia, R., Khaksar-Haghani, F., Javadian, N., & Tavakkoli-Moghaddam, R. (2014). Solving a multi-floor layout design model of a dynamic cellular manufacturing system by an efficient genetic algorithm. *Journal of Manufacturing Systems*, 33(1), 218-232. doi: 10.1016/j.jmsy.2013.12.005
- Kia, R., Shirazi, H., Javadian, N., & Tavakkoli-Moghaddam, R. (2015). Designing group layout of unequal-area facilities in a dynamic cellular manufacturing system with variability in number and shape of cells. *International Journal of Production Research*, 53(11), 3390-3418. doi: 10.1080/00207543.2014.986295

- Kouvelis, P., Kurawarwala, A. A., & Gutiérrez, G. J. (1992). Algorithms for robust single and multiple period layout planning for manufacturing systems. *European Journal of Operational Research*, 63(2), 287-303. doi: 10.1016/0377-2217(92)90032-5
- Kovács, G., & Kot, S. (2017). Facility layout redesign for efficiency improvement and cost reduction. *Journal of Applied Mathematics and Computational Mechanics*, 16(1), 63-74.
- Krishnan, K. K., Jithavech, I., & Liao, H. T. (2009). Mitigation of risk in facility layout design for single and multi-period problems. *International Journal of Production Research*, 47(21), 5911-5940. doi: 10.1080/00207540802175337
- Kulturel-Konak, S. (2007). Approaches to uncertainties in facility layout problems: perspectives at the beginning of the 21(st) century. *Journal of Intelligent Manufacturing*, 18(2), 273-284. doi: 10.1007/s10845-007-0020-10
- Kulturel-Konak, S., & Konak, A. (2015). A large-scale hybrid simulated annealing algorithm for cyclic facility layout problems. *Engineering Optimization*, 47(7), 963-978. doi: 10.1080/0305215X.2014.933825
- Kumar, R., & Singh, S. P. (2017). A similarity score-based two-phase heuristic approach to solve the dynamic cellular facility layout for manufacturing systems. *Engineering Optimization*, 49(11), 1848-1867. doi: 10.1080/0305215X.2016.1274205
- Kusiak, A., & Heragu, S. S. (1987). The facility layout problem. *European Journal of Operational Research*, 29(3), 229-251.
- Lenin, N., Siva Kumar, M., Islam, M. N., & Ravindran, D. (2013). Multi-objective optimization in single-row layout design using a genetic algorithm. *International Journal of Advanced Manufacturing Technology*, 67(5-8), 1777-1790. doi: 10.1007/s00170-012-4608-z
- Li, J., Tan, X., & Li, J. (2018). Research on Dynamic Facility Layout Problem of Manufacturing Unit Considering Human Factors. *Mathematical Problems in Engineering*, 2018, 1-13. doi: 10.1155/2018/6040561
- Liu, J., Wang, D., He, K., & Xue, Y. (2017). Combining Wang–Landau sampling algorithm and heuristics for solving the unequal-area dynamic facility layout problem. *European Journal of Operational Research*, 262(3), 1052-1063. doi: 10.1016/j.ejor.2017.04.002
- Manoochchetri, M., & Mohammadjafari, M. J. H. (2017). Developed a Mathematical Model for Solving the Two-Objective Dynamic Facility Layout Problem with Budget Constraints and Optimal Allocation of Buffer Size. 7(4), 1640-1654.
- Mazinani, M., Abedzadeh, M., & Mohebbali, N. (2013). Dynamic facility layout problem based on flexible bay structure and solving by genetic algorithm. *International Journal of Advanced Manufacturing Technology*, 65(5-8), 929-943. doi: 10.1007/s00170-012-4229-6
- McKendall, A. R., & Hakobyan, A. (2010). Heuristics for the dynamic facility layout problem with unequal-area departments. *European Journal of Operational Research*, 201(1), 171-182. doi: 10.1016/j.ejor.2009.02.028
- McKendall, A. R., Shang, J., & Kuppusamy, S. (2006). Simulated annealing heuristics for the dynamic facility layout problem. *Computers & Operations Research*, 33(8), 2431-2444. doi: 10.1016/j.cor.2005.02.021
- Meller, R. D., & Gau, K.-Y. (1996). The facility layout problem: Recent and emerging trends and perspectives. *Journal of Manufacturing Systems*, 15(5), 351-366. doi: dx.doi.org/10.1016/0278-6125(96)84198-7
- Mohammadi, M., & Forghani, K. (2014). A novel approach for considering layout problem in cellular manufacturing systems with alternative processing routings and subcontracting approach. *Applied Mathematical Modelling*, 38(14), 3624-3640. doi: 10.1016/j.apm.2013.11.058
- Moslemipour, G., & Lee, T. S. (2012). Intelligent design of a dynamic machine layout in uncertain environment of flexible manufacturing systems. *Journal of Intelligent Manufacturing*, 23(5), 1849-1860.
- Moslemipour, G., Lee, T. S., & Loong, Y. T. (2017). Performance Analysis of Intelligent Robust Facility Layout Design. *Chinese Journal of Mechanical Engineering (English Edition)*, 30(2), 407-418. doi: 10.1007/s10033-017-0073-9
- Murata, T., & Ishibuchi, H. (1994, 27-29th June.). *Performance evaluation of Genetic Algorithms for flow shop scheduling problems*. Paper presented at the Proceedings of the First IEEE International conference on Evolutionary Computation, Orlando, FL.

- Nageshwaraniyer, S. S., Khilwani, N., Tiwari, M. K., Shankar, R., & Ben-Arieh, D. (2013). Solving the design of distributed layout problem using forecast windows: A hybrid algorithm approach. *Robotics and Computer-Integrated Manufacturing*, 29(1), 128-138. doi: 10.1016/j.rcim.2012.06.007
- Neghabi, H., Eshghi, K., & Salmani, M. H. (2014). A new model for robust facility layout problem. *Information Sciences*, 278, 498-509. doi: doi.org/10.1016/j.ins.2014.03.067
- Nematian, J. (2014). A robust single row facility layout problem with fuzzy random variables. *International Journal of Advanced Manufacturing Technology*, 72(1-4), 255-267. doi: 10.1007/s00170-013-5564-y
- Nodem, F. I. D., Kenne, J. P., & Gharbi, A. (2011). Simultaneous control of production, repair/replacement and preventive maintenance of deteriorating manufacturing systems. *International Journal of Production Economics*, 134(1), 271-282.
- Nouri, M., Bekrar, A., Jemai, A., Trentesaux, D., Ammari, A. C., & Niar, S. (2017). Two stage particle swarm optimization to solve the flexible job shop predictive scheduling problem considering possible machine breakdowns. *Computers & Industrial Engineering*, 112, 595-606. doi: doi.org/10.1016/j.cie.2017.03.006
- Ousterhout, J. K. (2010). *Tcl and Tk toolkit* (2nd ed.): Addison Wesley.
- Pillai, V. M., Hunagunda, I. B., & Krishnan, K. K. (2011). Design of robust layout for Dynamic Plant Layout Problems. *Computers & Industrial Engineering*, 61(3), 813-823. doi: 10.1016/j.cie.2011.05.014
- Pongcharoen, P., Chainate, W., & Samranpun, C. (2007). Exploration of genetic parameters and operators through travelling salesman problem. *ScienceAsia*, 33(2), 215-222.
- Pourvaziri, H., & Naderi, B. (2014). A hybrid multi-population genetic algorithm for the dynamic facility layout problem. *Applied Soft Computing Journal*, 24, 457-469. doi: 10.1016/j.asoc.2014.06.051
- Pourvaziri, H., & Pierreval, H. (2017). Dynamic facility layout problem based on open queuing network theory. *European Journal of Operational Research*, 259(2), 538-553. doi: doi.org/10.1016/j.ejor.2016.11.011
- Rabbani, M., Farrokhi-Asl, H., Rafiei, H., & Khaleghi, R. (2017). Using metaheuristic algorithms to solve a dynamic cell formation problem with consideration of intra-cell layout design. *Intelligent Decision Technologies*, 11(1), 109-126. doi: 10.3233/IDT-160281
- Rezazadeh, H., Ghazanfari, M., Saidi-Mehrabad, M., & Sadjadi, S. J. (2009). An extended discrete particle swarm optimization algorithm for the dynamic facility layout problem. *Journal of Zhejiang University-Science A*, 10(4), 521. doi: 10.1631/jzus.A0820284
- Rosenblatt, M. J. (1986). Dynamics of plant layout. *Management Science*, 32(1), 76-86.
- Safari, E., & Sadjadi, S. J. (2011). A hybrid method for flowshops scheduling with condition-based maintenance constraint and machines breakdown. *Expert Systems with Applications*, 38(3), 2020-2029. doi: 10.1016/j.eswa.2010.07.138
- Sahin, R., & Turkbey, O. (2009). A new hybrid tabu-simulated annealing heuristic for the dynamic facility layout problem. *International Journal of Production Research*, 47(24), 6857. doi: 10.1080/00207540802376323
- Salmani, M. H., Eshghi, K., & Neghabi, H. (2015). A bi-objective MIP model for facility layout problem in uncertain environment. *International Journal of Advanced Manufacturing Technology*, 81, 1563-1575. doi: 10.1007/s00170-015-7290-0
- Samarghandi, H., Taabayan, P., & Behroozi, M. (2013). Metaheuristics for fuzzy dynamic facility layout problem with unequal area constraints and closeness ratings. *International Journal of Advanced Manufacturing Technology*, 67(9-12), 2701-2715. doi: 10.1007/s00170-012-4685-z
- Sbihi, M., & Varnier, C. (2008). Single-machine scheduling with periodic and flexible periodic maintenance to minimize maximum tardiness. *Computers & Industrial Engineering*, 55(4), 830-840. doi: 10.1016/j.cie.2008.03.005
- Schemeleva, K., Delorme, X., Dolgui, A., & Grimaud, F. (2012). Multi-product sequencing and lot-sizing under uncertainties: A memetic algorithm. *Engineering Applications of Artificial Intelligence*, 25(8), 1598-1610. doi: dx.doi.org/10.1016/j.engappai.2012.06.012
- Sethi, A., & Sethi, S. (1990). Flexibility in manufacturing: a survey. *International Journal of Flexible Manufacturing Systems*, 2(4), 289-328. doi: 10.1007/BF00186471

- Shafigh, F., Defersha, F. M., & Moussa, S. E. (2017). A linear programming embedded simulated annealing in the design of distributed layout with production planning and systems reconfiguration. *International Journal of Advanced Manufacturing Technology*, 88(1-4), 1119-1140. doi: 10.1007/s00170-016-8813-z
- Singh, S. P., & Sharma, R. R. K. (2006). A review of different approaches to facility layout problems. *International Journal of Advanced Manufacturing Technology*, 30, 425-433.
- Sooncharoen, S., Vitayasak, S. & Pongcharoen, P. 2015. Application of Biogeography-Based Optimisation for Machine Layout Design Problem. *International Journal of Mechanical Engineering and Robotics Research*, 4(3), 251-254. doi: doi.org/10.18178/ijmerr.4.3.251-254.
- Tavakkoli-Moghaddam, R., Javadian, N., Javadi, B., & Safaei, N. (2007). Design of a facility layout problem in cellular manufacturing systems with stochastic demands. *Applied Mathematics and Computation*, 184(2), 721-728. doi: doi.org/10.1016/j.amc.2006.05.172
- Tayal, A., Gunasekaran, A., Singh, S. P., Dubey, R., & Papadopoulos, T. (2017). Formulating and solving sustainable stochastic dynamic facility layout problem: a key to sustainable operations. *Annals of Operations Research*, 253(1), 621-655. doi: doi.org/10.1007/s10479-016-2351-9
- Tayal, A., & Singh, S. P. (2017). Designing Flexible Stochastic Dynamic Layout: An Integrated Firefly and Chaotic Simulated Annealing-Based Approach. *Global Journal of Flexible Systems Management*, 18(2), 89-98. doi: doi.org/10.1007/s40171-016-0140-6
- Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). *Facilities Planning* (Fourth ed.): John Wiley & Sons.
- Turanoğlu, B., & Akkaya, G. (2018). A new hybrid heuristic algorithm based on bacterial foraging optimization for the dynamic facility layout problem. *Expert Systems with Applications*, 98, 93-104. doi: doi.org/10.1016/j.eswa.2018.01.011
- Ulutas, B., & Islier, A. A. (2015). Dynamic facility layout problem in footwear industry. *Journal of Manufacturing Systems*, 36, 55-61. doi: doi.org/10.1016/j.jmsy.2015.03.004
- Ulutas, B. H., & Islier, A. A. (2009). A clonal selection algorithm for dynamic facility layout problems. *Journal of Manufacturing Systems*, 28(4), 123-131. doi: dx.doi.org/10.1016/j.jmsy.2010.06.002
- Vitayasak, S. (2011). *Multiple-Row Rotatable Machine Layout Using Genetic Algorithm*. Technical research report (in Thai), Naresuan University, Phitsanulok, Thailand.
- Vitayasak, S., & Pongcharoen, P. (2011). *Interaction of crossover and mutation operations for designing non-rotatable machine layout*. Paper presented at the Proceedings of the Operations Research Network Conference, Bangkok, Thailand.
- Vitayasak, S., & Pongcharoen, P. (2015). *Genetic Algorithm Based Robust Layout Design By Considering Various Demand Variations*. *Lecture Notes in Computer Science*, 9140, 257-265. doi: doi.org/10.1007/978-3-319-20466-6\_28
- Vitayasak, S. & Pongcharoen, P. (2016). Application of Genetic Algorithm for quantifying the affect of breakdown maintenance on machine layout. In: Sombatheera, C., Stolzenburg, F., Lin, F., Nayak, A., (eds) Multi-disciplinary Trends in Artificial Intelligence. MIWAI 2016. Lecture Notes in Computer Science, vol 10053. Springer. doi: doi.org/10.1007/978-3-319-49397-8\_18
- Vitayasak, S., & Pongcharoen, P. (2018). Performance improvement of Teaching-Learning-Based Optimisation for robust machine layout design. *Expert Systems with Applications*, 98, 129-152. doi: doi.org/10.1016/j.eswa.2018.01.005
- Vitayasak, S., Pongcharoen, P., & Hicks, C. (2017). A tool for solving stochastic dynamic facility layout problems with stochastic demand using either a Genetic Algorithm or modified Backtracking Search Algorithm. *International Journal of Production Economics*, 190, 146-157. doi: doi.org/10.1016/j.ijpe.2016.03.019
- Waeyenbergh, G., & Pintelon, L. (2009). CIBOCOF: A framework for industrial maintenance concept development. *International Journal of Production Economics*, 121(2), 633-640.
- Wang, G., Shin, Y. W., & Moon, D. H. (2016). Comparison of three flow line layouts with unreliable machines and profit maximization. *Flexible Services and Manufacturing Journal*, 28(4), 669-693. doi: doi.org/10.1007/s10696-015-9233-3
- Wang, H. (2002). A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research*, 139, 469-489.



- Wang, P. S., Yang, T., & Chang, M. C. (2017). Effective layout designs for the Shojinka control problem for a TFT-LCD module assembly line. *Journal of Manufacturing Systems*, 44, 255-269. doi: doi.org/10.1016/j.jmsy.2017.07.004
- Xiao, Y., Xie, Y., Kulturel-Konak, S., & Konak, A. (2017). A problem evolution algorithm with linear programming for the dynamic facility layout problem—A general layout formulation. *Computers and Operations Research*, 88, 187-207. doi: doi.org/10.1016/j.cor.2017.06.025
- Xiong, J., Xing, L., & Chen, Y. (2013). Robust scheduling for multi-objective flexible job-shop problems with random machine breakdowns. *International Journal of Production Economics*, 141(1), 112-126. doi: dx.doi.org/10.1016/j.ijpe.2012.04.015
- Yang, T., & Brett, A. P. (1998). Flexible machine layout design for dynamic and uncertain production environments. *European Journal of Operational Research*, 108(1), 49-64.
- Yin, X. F., & Khoo, L. P. (2011). An exact schema theorem for adaptive genetic algorithm and its application to machine cell formation. *Expert Systems with Applications*, 38(7), 8538-8552. doi: doi.org/10.1016/j.eswa.2011.01.055
- Zhao, Y., & Wallace, S. W. (2014). Integrated facility layout design and flow assignment problem under uncertainty. *Inform Journal on Computing*, 26(4), 798-808. doi: 10.1287/ijoc.2014.0599
- Zhao, Y., & Wallace, S. W. (2016). Appraising redundancy in facility layout. *International Journal of Production Research*, 54(3), 665-679. doi: doi.org/10.1080/00207543.2015.1030041